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# RESEARCH MEMORANDUM

A SUMMARY OF PRELIMINARY INVESTIGATIONS INTO THE  
CHARACTERISTICS OF COMBUSTION SCREECH IN  
DUCTED BURNERS

By Lewis Laboratory Staff

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**NATIONAL ADVISORY COMMITTEE  
FOR AERONAUTICS**

**WASHINGTON**

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## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUMA SUMMARY OF PRELIMINARY INVESTIGATIONS INTO THE CHARACTERISTICS  
OF COMBUSTION SCREECH IN DUCTED BURNERS

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## SUMMARY

Increasing demands for higher afterburner performance have required operation at progressively higher fuel-air ratios, which has increased the occurrence and intensity of screeching combustion. The onset of screech may be followed by rapid destruction of the combustor shell and other combustor parts. Because of its destructive characteristics, considerable effort has been expended to understand and eliminate screech. NACA work on the screeching combustion problem prior to November 1953 is summarized herein. These studies showed that resonant acoustic oscillations are a primary component of the screech mechanism in the burners thus far investigated. Detailed studies of frequency, amplitude, and phase relations were made in burners 6 to 37 inches in diameter; these oscillations were identified as a transverse mode. In various full-scale afterburners the observed frequencies were those to be expected from a transverse oscillation. The effects of design and operational variables on screech intensity have been investigated. Attempts to eliminate screech by reducing the driving potential of the gas stream were generally unsuccessful, but the use of an acoustic damper completely eliminated screech in all burner configurations in which it was used.

## INTRODUCTION

The increasing demand for higher performance from turbojet engine afterburners and ram-jet engine combustors has required operation of these combustors at the high temperatures obtainable only near stoichiometric fuel-air mixture ratios. The increased operating temperatures in combination with low altitude, or high altitude together with high flight speeds, has often led to the phenomenon known throughout the aircraft industry as screech. This phenomenon derives its name from the shrill scream or screech accompanying it. Other manifestations of screech are high-frequency pressure oscillations in the combustion zone, increased rate of flame propagation, usually improved afterburner combustion efficiency, higher operating temperatures of the combustor parts and shell,

and, under moderate to severe screeching conditions, rapid deterioration or failure of combustor shell, flame holder, and other combustor parts. An example of an afterburner failure produced by screeching combustion is shown in figure 1. Because of the severe deterioration of the combustor under screeching operating conditions, it has been essential that an understanding of the screech phenomenon be gained and that a method of controlling or eliminating screech be devised.

Many investigators have studied the screech problem (for example, refs. 1 to 7). From these investigations and others not yet published, several theories have been evolved in an attempt to describe the screech phenomenon. These theories have been based either on some phase of combustion kinetics, aerodynamics, or self-exciting acoustic resonance or on a combination of these. Under combustion kinetics, consideration has been given to phenomena similar to knock in reciprocating engines, detonation, flashback, and properties of the fuel such as flame speed. Among aerodynamic factors considered have been vortex strength, vortex interaction from flame holders, boundary-layer effects, and flow separation. Theories based on acoustical resonance have included longitudinal or organ-pipe vibrations, radial modes of vibration, and transverse modes of vibration.

The NACA Lewis laboratory has investigated most of these possibilities. The evidence collected, although it does not completely describe screech, has strongly indicated some of the predominant characteristics of screech. The present paper summarizes the more important phases of the analytical work, small and large duct experiments, and full-scale engine investigations conducted at the NACA Lewis laboratory prior to November 1953. These results are compared with the works of other experimenters to correlate the predominant characteristics of screech. A mechanism for control or elimination of screech is described.

### SYMBOLS

The following symbols are used in this report:

- a      speed of sound
- B      constant of integration (eq. (1))
- d      gutter radius
- f      frequency, cps
- h      function defined by equations (1) and (2)
- $J_n, N_n$       Bessel functions of the first and second kind, respectively

- $n, m$  mode numbers such that  $n$  and  $m+1$  are the number of nodal diameters and nodal circles, respectively
- $P'$  pressure fluctuation
- $R, R_i$  center-wall and inner-body radii, respectively
- $t$  time
- $x, r, \theta$  cylindrical coordinates
- $\alpha, \alpha_{nm}$  reduced frequency determined by solving equation (5) or (7)
- $\beta$  amplification numbers (eq. (8))

### ANALYSIS

Preliminary experimental investigations at the NACA, as well as information available from work done elsewhere, led to the belief that acoustic oscillations were present during screeching combustion. Hence, coincident with the continuing experimental studies, a theoretical analysis has been made of the possibilities of sonic resonance in a combustor. Once it is assumed that acoustic resonance may be present in a screeching combustor, the problem becomes one of finding what forms these oscillations may take and which modes are most likely to occur. To this end, as a model, there may be considered a circular cylindrical duct having, in the steady state, a relatively slow uniform through flow and an axial steady temperature variation (and hence axial variation in the speed of sound  $a$ ). The hardware in the combustor may reasonably be assumed irrelevant provided the chamber is relatively clean downstream of the flame holder. Within these assumptions, the unsteady pressure fluctuation  $P'$  must satisfy (the subscripts denote differentiation)

$$a^2 \left( P'_{rr} + \frac{P'_r}{r} + \frac{P'_{\theta\theta}}{r^2} \right) + (a^2 P'_x)_x = P'_{tt}$$

Solutions of this equation may be written

$$P' = e^{i(2\pi f t + n\theta)} \left[ J_n(\alpha_{nm} \pi r/R) + B N_n(\alpha_{nm} \pi r/R) \right] h(x) \quad (1)$$

where  $\alpha_{nm}$  (hereinafter written simply  $\alpha$ ) is chosen such that there is no flow across the chamber wall  $r = R$  and where  $h(x)$  is such that

$$(a^2 h_x)_x + \pi^2 \left[ 4f^2 - \left( \frac{a\alpha}{R} \right)^2 \right] h = 0 \quad (2)$$

$J_n$  and  $N_n$  are the Bessel functions of the first and second kinds, respectively. If a more complex model had been assumed, say, one in which the steady-state pressure and axial velocity were assumed to vary with  $x$ , then equation (1) would still apply but equation (2) would be more involved. This remark would also apply if a uniform axial through flow of large magnitude were included, or if a longitudinally varying heat release were considered.

The integers  $n$  and  $m$  may be related to the number of pressure nodes in the oscillation. Thus,  $n$  is the number of nodal lines (which lie along diameters) and  $m + 1$  is the number of nodal circles.

### Modes of Acoustic Resonance

Equation (1) embraces all the possible resonant oscillations in a circular cylinder. These are well known (cf. ref. 8) but will be briefly described herein. The solution involving  $N_n$  is rejected because it is singular at the pipe axis and hence is inadmissible when there is no centerbody. For simplicity of description, the speed of sound is assumed constant. The modes are:

1. Purely longitudinal (organ-pipe). - If  $a$  is constant, then equation (2) has the solution

$$h = e^{+i\pi \sqrt{\frac{4f^2}{a^2} - \frac{\alpha^2}{R^2}} x} \quad (3)$$

If  $n$  and  $\alpha$  are chosen to be zero, then

$$P' = e^{2\pi i f(t \pm x/a)} \quad (4a)$$

2. Radial and transverse. - If  $2fR/a = \alpha$ , then a permissible solution of equation (2) is  $h = 1$ . In such case

$$P' = e^{i \left[ \left( \frac{\pi \alpha a}{R} \right) t \pm n \theta \right]} J_n(\pi \alpha_{nm} r/R) \quad (4b)$$

It may be noted that for  $n = 0$ , there are obtained the radial modes, while for  $n \neq 0$  there are found what will be called the transverse modes. In figure 2, there are sketched the particle paths and pressure amplitude contours (mutually orthogonal) for the (1,0) transverse mode. The notation (1,0) means  $n=1$ ,  $m=0$ . Pressure amplitude contours are shown in figures 3 and 4. The radial (0,m) modes have a pressure maximum at the center of the duct while all the other (transverse) modes show

zero pressure amplitude at that point. In figure 3, the wall would be at station a, b, c, etc., depending on whether the first, second, third, or a higher radial mode occurred. It may also be observed that the  $(n,1)$  modes (fig. 4(b)) contain the pattern for the  $(n,0)$  modes (fig. 4(a)) as a core inside the dashed circle.

3. Combined lateral-longitudinal. - If  $a = \text{constant}$ , the combined modes may be written:

$$P' = e^{i \left( 2\pi f t \pm \theta \pm \pi \sqrt{\frac{4f^2}{a^2} - \frac{\alpha^2}{R^2}} x \right)} J_n(\alpha r \frac{r}{R}) \quad (4c)$$

If, in the three cases described, the speed of sound had been assumed variable, results similar to those given would be obtained except that the longitudinal factor  $h(x)$  in the wave would be more complex and not, in general, easily represented.

It may be important for the purpose of experimental identification to distinguish between the effect produced by a longitudinal (organ-pipe) mode and the effect which may be produced by temperature. The organ-pipe mode (fig. 5(a)) is such that in a given wave length there is symmetry about the midpoint and, at a given time, the spatial average of the pressure fluctuation  $P'$  is zero. The effect of temperature may be something quite different. Figure 5(c) shows the pressure amplitude profile found when equation (2) was integrated numerically for the temperature profile of figure 5(b). In this case the effect of temperature was simply to modify an otherwise constant pressure amplitude. This latter effect (of modifying the longitudinal pressure profile) must be present when the chamber temperature (and hence the speed of sound) varies.

In a practical combustor the manner in which the oscillation is driven will modify the motion. If the motion is driven in one region of the burner by, say, a combustion oscillation, it may be that the oscillation in another region will exhibit a phase lag relative to the region where the driving occurs. This is simply because the motion is formed of waves originating at the driving station and these will take an appreciable time (relative to the period of oscillation) to reach another portion of the chamber.

### Resonance Frequencies

The constant  $\alpha_{nm}$  is the value of the argument of  $J_n$  such that

$$\frac{d}{dr} \left[ J_n(\alpha r r/R) \right]_{r=R} = 0 \quad (5)$$

and equals the reduced frequency  $2\pi R/a$  for purely radial or transverse oscillations. Remembering that  $J_n$  is an oscillating function of its argument, it follows that, for any  $n$ , an infinite sequence of values

( $m$ ) of  $\alpha$  exist for which  $\frac{d}{dr} \left[ J_n \left( \frac{\alpha r}{R} \right) \right]_{r=R} = 0$ . This sequence of  $m$ 's

and  $n$ 's yields a doubly-infinite set of possible reduced frequencies. If a longitudinal oscillation is included (eq. (4c)), the frequency of the mode is altered and a third infinity of possible frequencies is introduced. In general, the frequency is found from equation (4c) and is given by

$$f = \frac{a}{2} \sqrt{\left( \frac{\alpha}{R} \right)^2 + \left( \frac{n_x}{l} \right)^2} \quad (6)$$

where  $n_x/l$  is the half wave length of the longitudinal mode. For example, if the first (1,0) transverse mode occurs, the frequency in a 6-inch duct would be about 3000 cycles per second with usual burner temperatures. If this mode appears in conjunction with the first longitudinal mode (assuming that the ratio of diameter to length is  $1/3$ ), the transverse frequency will be raised about 100 cycles per second.

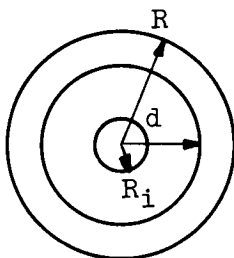
At this point, it is appropriate to note that the wave systems discussed are for standing waves, that is, for waves having fixed nodal diameters. It is also possible to have transverse traveling waves, such that the amplitude of the wave pattern is fixed but the whole pattern rotates. The discussion of frequencies given previously applies equally to standing and traveling waves.

Centerbody. - In order to take into account a central body, the solution must include both Bessel functions (eq. (1)). In such a case, the reduced frequency  $\alpha$  is determined by solving the equation

$$\left[ \frac{\frac{d}{dr} J_n \left( \frac{\alpha r}{R} \right)}{\frac{d}{dr} N_n \left( \frac{\alpha r}{R} \right)} \right]_{r=R} = \left[ \frac{\frac{d}{dr} J_n \left( \frac{\alpha r}{R} \right)}{\frac{d}{dr} N_n \left( \frac{\alpha r}{R} \right)} \right]_{r=R_i} \quad (7)$$

where  $R_i$  and  $R$  are the wall radii. This expression is found from the condition that the radial velocity and hence  $\partial P'/\partial r$  vanish at the walls. In general, it follows from the solution of this equation that for the first radial mode (0,1), the presence of a centerbody increases the frequency, while for a transverse mode of the form (n,0) the frequency will be decreased. For other modes, the frequency will be either increased, decreased, or unaltered, depending on the ratio of centerbody to outer wall diameter. Although the theory assumes that the centerbody extends to the ends of the chamber, the results are probably valid if it extends a substantial distance downstream of the flame holder.

Heat addition. - It appears that when screech occurs, there is a violent disturbance of the flame behind the gutters. This occurrence should be accompanied by a variation in the local heat release. If the local pressure or temperature rises, the heat release should increase in this region of unsteady burning. The heat release in this disturbed region (assumed here to be annular) will act on the remaining fluid somewhat in the manner of a mass source; thus, the energy addition will cause an incremental flow away from the annulus, which for a thin annulus may be represented by a radial velocity discontinuity at that station ( $d$  in the following sketch). The temperature fluctuations are



related to the pressure changes. It is assumed for simplicity that there are no time lags involved. With this model of the effect of annular heat addition, two solutions, similar to equation (1) and applying on either side of  $r = d$ , are found. However, in this case the frequency  $\alpha a/2R$  is complex, and the following expression may be written:

$$P' = e^{\beta t} \cos\left(\frac{\pi \alpha a t}{R}\right) \text{ (function of } r, \theta) \quad (8)$$

where  $\beta$  is always positive and real and  $\alpha a/2R$  is the frequency found from equation (7), which applies in the absence of this added disturbance.

The relative amplification is plotted for various cases in figures 6 and 7. The factor plotted is  $\beta$  divided by a constant depending on the pressure and temperature sensitivity of the flame. From figure 6, it appears that the radial mode is most likely for burning near the axis; otherwise, a transverse mode should occur. Further, the driving is strongest for the transverse modes if the heat is added near the outer wall. The main trend to be observed in figure 7 is that the driving (of the first transverse mode) increases with gutter diameter regardless of the centerbody diameter. If, as may be the case, the driving of the oscillation is associated with unsteady burning in the high-shear region near the wall, this analysis would indicate a stronger preference for a transverse mode. It should be emphasized here that the total heat release has been assumed the same for all gutter positions. This assumption represents a highly idealized picture, particularly for locations near the wall and near the center of the duct.



Although it appears that for burning near the outer wall, the higher ( $n$ ) modes are driven most strongly, other factors tend to counteract this. It has been shown (see, for example, ref. 12) that, as might be expected, viscous damping of a transverse wave at the wall increases with frequency. Hence, it is reasonable to expect that for a flame holder near the axis, the radial mode is most likely; while for a configuration wherein the gutter is far from the axis, one of the lower-frequency transverse modes is most probable.

If this model had included the effect of an induction time lag, which is a function of the inlet conditions, flame holder, fuel, and the like, the triply infinite set of possible frequencies of oscillation would become a virtually continuous spectrum, especially for the higher modes. Hence, identification of a mode by means of phase relations, rather than by frequency, is likely to be more fruitful. The lowest possible frequency (excluding longitudinal modes) remains that of the first transverse mode (1,0).

Further, it should be remembered that the analysis described here is a linear one based on small disturbances. In the actual screeching combustor, the oscillations are very large and the phenomenon is certainly nonlinear. In such a case it may be expected that such things as phase relations may be somewhat modified, although the results indicated by the present analysis should be reasonably accurate. When there is a high average through-flow velocity, the wave system may deviate sufficiently from the simplified picture given here to give appreciable changes in frequency. This point is discussed further in reference 2.

#### Summary of Theoretical Predictions

1. The extreme "density" of possible resonant-pipe oscillations suggests that experimental identification of acoustic mode not be attempted on the basis of frequency alone. Rather, phase relations should be found. Because of variations of fuel, gutter geometry, inlet conditions, and the like, the coupling of unsteady heat release with pressure oscillation will probably cause appreciable variations in the frequency of acoustic oscillations. Also, the theoretical frequencies are dependent upon some average chamber temperature, a quantity which may be very difficult to determine accurately.

2. If energy is added to the oscillation at an annulus near the center of the duct, radial oscillations appear most probable; if near the outer shell, transverse modes are more probable.

3. The presence of a centerbody will not necessarily increase the frequency of lateral oscillation; in fact, if a transverse oscillation of the type ( $n,0$ ) occurs, the frequency must be reduced.

## EXPERIMENTAL DETERMINATION OF SCREECH MECHANISM

Three modes of acoustical resonance were discussed in the preceding section as possible elements of the screech mechanism. Concurrently with the analytical work, the screech mechanism was experimentally investigated in ducted burners having diameters of 6, 8, 14, 20, and 26 inches. These studies included amplitude, frequency, and phase measurements during screeching combustion.

Amplitude distribution. - The relative pressure amplitude during screech at various positions across the diameter of the 6-inch combustor of reference 1 is shown in figure 8 for a survey made  $3/4$  inch downstream of the flame holder. The amplitude exhibits a pronounced dip near the center of the duct. This is the amplitude pattern to be expected with a transverse mode of oscillation; such a pattern could not result from radial or longitudinal oscillations.

Figure 9 shows values of pressure amplitude at the wall of the 6-inch burner at various positions along the length of the burner. A peak exists in the pressure amplitude 4 to 6 inches downstream of the flame holder. The pattern of amplitude against burner length shown in figure 9 does not indicate the presence of a standing longitudinal wave. The region of maximum amplitude just downstream of the flame holder lies where the maximum heat-release rate might be expected. If there existed a combined transverse and longitudinal oscillation, and if the longitudinal component is to appreciably affect the indicated frequencies, the half wave length would have to be on the order of a diameter (eq. (6)). With a half wave length of this magnitude, multiple pressure nodes would occur in the 38-inch length surveyed in figure 9. Since multiple nodes are not evidenced in figure 9, there exist no longitudinal components which can appreciably affect the frequency. The screech frequency can therefore be expressed by the relation

$$f = \frac{\alpha c}{2R}$$

Frequency. - An observed screech frequency in the 6-inch burner of approximately 3300 cycles per second was obtained at an over-all equivalence ratio of 0.94 and an inlet temperature of  $800^{\circ}$  F. This frequency can be produced by the first transverse mode (1,0) of oscillation ( $\alpha = 0.586$ ) if the speed of sound is 2920 feet per second, or by the second transverse mode (2,0) ( $\alpha = 0.972$ ) if the speed of sound is 1710 feet per second. These values for the speed of sound correspond to average temperatures of  $3560^{\circ}$  and  $800^{\circ}$  F, respectively. The higher of these temperatures approaches the theoretical flame temperature; the lower is the temperature of the inlet gas. Considerations of screech frequency therefore indicate that the oscillation could consist of the first transverse mode in the hot gas or the second transverse mode in the inlet stream.

For transverse modes of oscillation, the pressure will be out of phase on opposite sides of the combustor for odd values of  $n$  and in phase on opposite sides of the combustor for even values of  $n$ , along any diameter except an antinodal diameter. Phase measurements should therefore make it possible to determine whether the first (1,0) or the second (2,0) transverse mode occurs in the 6-inch burner.

Phase measurements. - By means of the special microphones for studying phase relations, described in reference 1, vertical diametric surveys of pressure amplitude were made at three distances downstream of the flame holder in the 6-inch burner. The phase of the pressure signal relative to the signal obtained at a point near the flame holder is shown in figure 10. The  $180^\circ$  phase shift across a diameter indicates that the first transverse mode of oscillation persisted in the burner. The data of figure 10 also indicate a phase shift along the length of the burner. This is further shown by the data in figure 11, which presents the relative phase of the pressure signal at various positions along the length of the burner. A pronounced phase shift in the vicinity of the flame holder indicates that in this region the waves have appreciable longitudinal components. The absence of a phase shift in the hot gases farther downstream of the flame holder indicates the presence of pure transverse oscillation in this region.

Phase measurements in the 26-inch ducted burner are shown in figure 12. Figure 12(a) shows oscilloscope traces with four microphone pressure pickups equally spaced on the outer wall of the burner. Pickups 1 and 3 were located at opposite ends of the diametric V-gutter flame holder and showed little variation in the burner pressure. Pickups 2 and 4 were located at opposite walls of the burner on an axis at right angles to the flame holder, and these pickups indicated marked variations in pressure which were approximately  $180^\circ$  out of phase between the two pickups. Figure 12(b) shows additional oscilloscope traces obtained with unequally spaced microphone pickups as indicated. Pickups 1 and 4, which were aligned with the main axis of the flame holder, indicated little variation in pressure. Pickup 2, which was midway between pickups 1 and 4, showed a marked variation in pressure. Pickup 3, which was located between pickups 2 and 4, showed a variation in pressure in phase with that indicated by pickup 2, but having smaller magnitude. The oscilloscope traces of figures 12(a) and 12(b) are what would be expected with the first standing transverse mode (1,0) of oscillation in the burner and with an antinodal line coincident with the axis of the flame holder.

Similar pressure records obtained with a different (5-inch width) flame holder are shown in figure 12(c). Pressure pickups 1 and 4, which were located on an axis normal to the flame holder showed very little variation in pressure. Pickup 3 (located on the flame-holder axis) and pickup 2 (located between pickups 1 and 3) indicated marked variations

in pressure which were in phase between these two pickups. These data indicate the existence of the standing (1,0) mode of oscillation with an antinodal line normal to the axis of the flame holder.

The data of figure 12 indicate the existence of the standing transverse mode of oscillation. In the 6-inch burner with a central single-cone flame holder, however, stroboscopic motion pictures indicate the existence of a traveling (spinning) transverse oscillation. Apparently either the standing or the traveling oscillations can occur; the spinning oscillation may be favored when the flame holder is symmetric.

Phase relations between flame pressure pulses. - With two ionization gaps located  $180^\circ$  apart,  $3/4$  inch downstream of the flame holder, and extending  $3/4$  inch from the burner walls, the signals shown in figure 13 were obtained in the 6-inch burner. The flame striking the ionization gaps was  $180^\circ$  out of phase on opposite sides of the burner. Simultaneous measurement of pressure and flame-produced ionization near the flame holder showed that the outward flame-front motion was nearly in phase with the pressure at this station. The small phase difference between the pressure and ionization traces in figure 13(b) is just that found between pressure measurements at the two stations. On the basis of these phase measurements and measurements similar to those shown in figure 11, a time sequence of events in the screech cycle can be constructed as shown in figure 14. The relation between the pressure and the flame-front displacement is that expected with a transverse oscillation. Also, it is of interest that the region of maximum amplitude separates the downstream region having a uniform transverse oscillation from a region in which waves appear to be propagated upstream at approximately the speed of sound relative to the moving gas.

#### SPECULATION REGARDING SCREECH MECHANISM

The data thus far indicate that the gas in those burners investigated does, in fact, execute a transverse oscillation during screech. It yet remains to find the cause and origin of screech. Obviously, some source of energy or driving potential is required to maintain the resonant oscillations. If this source of energy can be found, screech can be prevented by reducing or removing the energy source. Two sources of energy are available in the burner: (1) the kinetic energy in the flowing gas stream, and (2) the chemical energy released during the combustion process. Of these two sources, the chemical energy is far greater. In order for this energy to be made available to overcome damping and maintain the oscillations at a high amplitude, it is necessary for it to be involved in some time-varying work cycle. The criterion proposed by Rayleigh (ref. 10) is that if the heat input occurs at locations where the pressure varies and at a time where the pressure is near its maximum, then the driving is a maximum. For the case where the oscillations are

driven by the kinetic energy of the flowing stream, the heat release plays a part in intermittently storing and releasing this kinetic energy in such a manner that the oscillation is maintained (ref. 13). In either event, it is obvious that the oscillation may be driven only when the heat release undergoes a variation with time. This may be brought about in many ways.

A coupling between the chemical reaction and the acoustic oscillations could result from the effect of pressure and temperature on the chemical kinetics. The rate of energy release per unit volume in high-speed combustion equipment has been shown to increase with increase in pressure and temperature (refs. 14 and 15). The increase in pressure and temperature accompanying the arrival of each pressure pulse at the flame zone could therefore be expected to increase the heat-release rate. This coupling is described in the analysis section in the discussion leading to equation (8). For small oscillations, the effect is possibly negligible, but for large waves the increased heat-release rate could be very important in maintaining screech.

Increases in flame-front area resulting from pressure pulses could also account for the necessary coupling. That flame-front disturbances do exist is evident from the data of figures 13 and 14 as well as from the schlieren photographs shown in reference 3. If the rate of heat release is proportional to the product of the normal laminar flame speed and the flame-front area, wrinkling of the flame due to the action of pressure pulses could result in the necessary coupling. There is a strong possibility that a flame-front extension is caused by the scattering of waves at the flame holder and hence will depend on flame-holder size. This mechanism might amplify small oscillations and thus be important at the onset of screech.

Additional coupling between the chemical reaction and the acoustic oscillations may occur because of the phenomenon of detonation. However, no definite evidence of its presence has been found in afterburners.

The energy in the oscillation is lost in at least three ways. Energy is radiated upstream in an amount proportional to the gas density and the cross-sectional area of the duct; energy is conveyed out of the exhaust nozzle in an amount proportional to the mass rate of flow; and energy is imparted to the wall of the burner itself through friction and flection. All these rates of energy loss will be dependent on the square of the pressure amplitude.

The energy supplied to the oscillation by the mechanisms already discussed varies with pressure amplitude in different fashions. At the onset of screech the flame distortion due to scattering of waves at the flame holder may be the most important driving factor. As the amplitude builds up, this driving mechanism might be superseded by the effect of increased heat release due to adiabatic compression.

There are certain beneficial aspects of screech which make it worth while to consider whether or not a controlled screech might be desirable. Often, an increased combustion efficiency accompanies screech. Another advantage is the possible gain in over-all cycle efficiency for a given thermal efficiency. A gain in cycle efficiency might occur because more of the heat is released at a higher pressure level during screech. It is not known how much, if any, of such energy is available beyond that required to drive the oscillation.

#### EFFECT OF OPERATIONAL VARIABLES ON SCREECH LIMITS AND INTENSITY

Pressure. - The effect of pressure on screech amplitude in the 6-inch burner is shown in figure 15. The peak-to-peak pressure amplitude showed a general increase with increase in burner pressure. The air flow rate is noted for each data point of figure 15. At an air flow of 1.5 pounds per second, the pressure limit for screech was 20 inches of mercury; below this pressure, screech was not encountered. At the screech limit the combustor screeched intermittently; the short burst of screech at this limit had peak-to-peak amplitudes of 14 inches of mercury as indicated in figure 15.

The effect of pressure on the range of fuel-air ratios over which screech was encountered in a 36-inch-diameter afterburner is shown in figure 16. The afterburner construction details are shown in figure 17. The range of fuel-air ratios bracketing the screech zone increased progressively as the combustor pressure was increased. This is in agreement with the expectation that screech will be more prevalent when there is more energy available for driving.

No detailed measurements have been made of variations in frequency with pressure; sufficient observations have been made, however, to ascertain that only small changes in frequency occur as pressure is varied.

Flow rate. - The 6-inch burner screeched throughout most of its operating range, as shown in figure 18. Screech was encountered at progressively lower pressure as gas flow rate was decreased. During the screech, the combustion efficiency was 90 to 100 percent; the efficiency dropped abruptly by approximately 35 percent and the pressure by 17 percent when screech ceased. This abrupt change is indicated by the jump band in which stable operation was impossible.

No effect of flow rate on screech frequency was observed in the 6-inch burner.

Fuel-air ratio. - The effect of fuel-air ratio on screech limits for the 36-inch-diameter afterburner is shown in figure 16. For each pressure the afterburner screeched over a range of fuel-air ratios corresponding to the highest combustor-outlet temperatures.

The effect of fuel-air ratio on screech frequency in the 6-inch burner was as follows: Maximum frequency of 3500 cycles per second was obtained at a fuel-air ratio of 0.076. Screech frequency decreased as fuel-air ratio was decreased below this value. The frequency was 3350 cycles per second at a fuel-air ratio of 0.063 and 2800 cycles per second near the lean blow-out limit. These results are in agreement with the expectation that the screech frequency should increase with increase in sound speed or temperature of the combustion gases.

Burner length and diameter. - The length of the 6-inch burner could be varied from 34 to 45 inches by altering the position of the flame holder upstream of the exhaust nozzle. No appreciable change in screech frequency accompanied changes in flame-holder position. At one position of the flame holder, a longitudinal mode of oscillation appeared. This longitudinal oscillation did not replace the screech but merely accompanied and modulated it.

The chief result of changing the burner diameter was found to be a change in the screech frequency, the screech frequency varying inversely with burner diameter for most cases. Screech frequencies reported in the literature (refs. 4 to 7) for various full-scale afterburners can be explained by assuming transverse oscillation in the combustors. Figure 19 shows a plot of screech frequency as a function of combustor diameter. The theoretical screech frequencies for various modes of transverse oscillation in the hot gases are indicated by bands on the figure. Bands rather than discrete lines are shown to allow for variations in gas temperatures. The experimental points lie within the range of frequencies theoretically possible with transverse oscillations. The oscillations in the 6- to 20-inch combustors (refs. 1 to 3) correspond to the first transverse mode in the hot gases. For the larger combustors, higher modes have been experienced. In all cases in which phase measurements were made, the mode indicated by such observation was the same as that indicated on a frequency basis. The only data falling outside the theoretical range in figure 19 are some of the data for the 8-inch burner in which very high through velocities were used. Under these circumstances, as suggested in the analysis section and discussed further in reference 2, it is reasonable to expect that the measured frequencies will deviate from the theoretical ones. This low frequency may be partly due to the reduced combustion efficiency caused by the high through velocity but cannot be entirely explained by this phenomenon.

In reference 3 it was noted that an increase in frequency occurred when a centerbody downstream of the flame holder was removed. A transverse mode would allow such an effect, whereas a radial mode would not. The theoretical frequency with the centerbody used in reference 3 and the observed frequencies are also given in figure 19.

## SCREECH PREVENTION

The tendency of a combustor to screech can be reduced in two ways: (1) by reducing the driving potential, and (2) by increasing the damping potential of the combustor. In the following section, various afterburner configuration changes which might affect the driving potential will be discussed, while the adaptations based on damping will be treated in a later section.

## Reduction of Driving Potential

In general, the driving potential can be reduced by designing the combustor so that the principal combustion zones do not coincide with regions of maximum pressure amplitude, for example, near the walls for transverse modes. The driving potential might also be reduced by altering the chemical composition of the reacting mixture so that the reaction rate will be relatively insensitive to changes in pressure and temperature, or so that an appreciable time lag precedes any marked change in the reaction rate. Sufficient understanding of the screech driving mechanism and of the kinetics of the chemical reaction is not available to indicate practical schemes for tailoring the combustor and the fuel to take advantage of these principles. Consequently, attempts to reduce the driving potential must, at this time, be based on trial-and-error procedures in which those design features which might affect the driving potential are varied.

Many of the combustor design modifications described in this section of the report were made prior to the identification of the nature of combustion screech. Some of the design factors discussed in this section might induce changes in the damping potential of the combustor; however, their primary effect is believed to be on the driving mechanism. These design changes represent various exploratory researches into the aerodynamic and chemical characteristics of a combustor to try to find what factor might be the source or cause of screech. For example, the velocity distribution described in the following paragraphs involves, of course, aerodynamic considerations.

Velocity distribution. - The use of turbine-outlet antiwhirl vanes to improve the afterburner-inlet gas velocity profile removed the tendency to screech for the configuration of figure 17. Whirl in this engine had been as high as  $30^\circ$  counter to turbine rotation. The improvement in velocity profile with the addition of the antiwhirl vanes is shown in figure 20(a), and the accompanying change from a screeching to nonscreeching combustion is shown by the bar graphs of figure 20(b). Although improving the velocity profile at the afterburner inlet eliminated the screech in the configuration of figure 17, screech could not be eliminated in the afterburner of figure 21 by the use of antiwhirl vanes, vortex generators, or improved diffusers to improve the velocity profile.



Experience with several afterburners, including that of figure 21, has shown that burners having a strong tendency to screech are not greatly helped by improving velocity profiles. Further evidence that good velocity profile will not assure screech-free combustion is provided by the fact that screech is readily obtained in the 6- and 26-inch-diameter ducts discussed earlier, even though there were no diffuser inner cones and the velocity profiles were quite flat.

The investigation reported in reference 4 associated screech with combustion in low-velocity regions such as separated regions or vortex sheets in the wake of struts in the fuel mixing zone. In these experiments combustion was observed on the surface of the diffuser inner body. (Other investigations have also shown combustion to exist in some burner installations on the lee side of support struts or along the outer wall of the diffuser.) The velocity near the diffuser inner-cone wall was less than 90 feet per second as compared to a peak gas velocity of nearly 600 feet per second.

Several afterburner configurations were investigated to determine the validity of the impression that screech was primarily associated with combustion in the low-velocity regions in the fuel mixing zone. In several of these configurations fuel injectors were moved radially outward to remove any fuel from the low-velocity region along the inner cone and thus preclude combustion in this region. One example (configuration A, fig. 21) had the fuel-injection bars mounted  $15\frac{1}{4}$  inches upstream of the flame holder. The fuel-injection bars used for this phase of the investigation had the innermost fuel-injection orifice  $5\frac{1}{8}$  inches from the inner body. Screeching combustion was encountered with this configuration at a burner-inlet pressure of about 4000 pounds per square foot. Visual observation through a quartz window verified that there was no burning along the inner body at any time.

These observations are typical of those made with several other configurations investigated. In addition, the 26-inch duct burner without inner body and with fuel injection maintained several inches from the outer wall, so that combustion could not occur in the vicinity of any wall, also screeched. It was concluded, therefore, that screeching combustion was not necessarily associated with burning along the diffuser inner body or in other low-velocity regions in the fuel-mixing zone. The possibility of such combustion driving screech in some combustors, however, should not be ignored, since data of reference 4 and other evidence indicated that flames may occur in a separated flow region adjacent to shell and inner body walls concurrently with screech.

Fuel distribution. - Several investigations of screech have been conducted such as that of reference 5, in which the effects on screech of large variations in fuel distribution were studied. In general, screeching combustion could not be eliminated by changes in fuel distribution. This insensitivity of screeching combustion to fuel distribution was particularly true with a reasonably uniform diffuser-outlet velocity profile.

Exceptions to the absence of a fuel distribution effect were encountered only with a severe diffuser-outlet velocity gradient such as that of configuration C (fig. 22). In this afterburner, fuel-injection bar configurations 1 and 2 provided fuel injection across the entire diffuser passage to within about 1/2 inch of the inner-body wall, whereas configurations 3 and 4 injected fuel to within approximately  $1\frac{1}{2}$  inches of the inner body. Shifting the fuel concentration radially outward away from the inner body (fuel-injection bar configurations 3 and 4) eliminated the screech previously encountered (configurations 1 and 2) at an afterburner-inlet total pressure of 4200 pounds per square foot. This exception indicates that when the afterburner-inlet velocity gradient is severe, alterations in radial fuel distribution may be effective in eliminating screech. (The possibility of unsteady combustion upstream of the flame holder was considered in this case, but no flame could be observed upstream through observation windows in the afterburner shell.)

It has also been observed that even with good velocity profiles a reduction in fuel-mixing length (distance fuel-injection bars are located upstream of flame holder) will reduce the tendency for screech. This method of eliminating screech, however, is in general not a good method of solving the problem since it is not always effective; in addition, as a result of reduced mixing of fuel and air and reduced vaporization in the mixing zone, the combustion efficiency is generally impaired. Such a reduction in screech tendency may be due entirely to the increased time lag accompanying energy release in the chamber.

Fuel characteristics. - A limited number of fuel variations have been investigated with regard to screech tendencies of the afterburner. Fuels purchased under specifications MIL-F-5624A, grades JP-3 (Reid vapor pressure, 5.5 lb/sq in.) and JP-4 (Reid vapor pressure, 2.6 lb/sq in.) showed no difference in screech limits in a 37-inch-diameter afterburner. If, however, the fuel system had been located close to the flame holder, an increased fuel volatility might have increased the heat release (driving potential) in the primary combustion zone. In addition, since it has been suggested that screech could be driven by a detonation type of disturbance, aviation tetraethyl lead was added to the JP-3 fuel (5.3 ml/gal) as a detonation suppressor. The addition of the lead had no effect on the screech limits of the afterburner.

Flame-holder geometry. - Of the almost infinite number of variations in flame-holder geometry possible, it has been feasible to correlate only a few of these variations with tendency to screech. No consistent trend has been found with tendency for screech with such variables as position of flame holders with respect to burner wall, flame-holder configuration (diametrical, circumferential, and radial flame holders), number of flame holders, or gutter shape. However, a very definite trend has been found in both the large-scale and small-scale duct work and in full-scale afterburners with gutter width or size. An example of the effect of flame-holder width and flame-holder blockage on screech limits in the 36-inch-diameter afterburners is shown in figure 23. With gutter widths of approximately  $2\frac{1}{8}$  inches, screech was not encountered at burner-inlet total pressures up to 4070 pounds per square foot. With the outer gutter width increased to  $3\frac{1}{16}$  inches, screech was encountered at 2240 pounds per square foot burner-inlet pressure at fuel-air ratios above 0.04. The  $5\frac{3}{4}$ -inch-width gutter screeched over the entire range investigated at 2240 pounds per square foot. Observations such as the foregoing indicate that flame-holder gutter width and blockage are factors in controlling screech.

Additional evidence of the effect of gutter width on screech is found in a statistical summary that has been made of the flame-holder configurations operated in the investigation of the burner shell of figure 17. This summary is shown in figure 24, where the vertical scale indicates the number of different configurations in which a flame holder of a given width was incorporated. From this summary, which includes gutter widths from  $1\frac{1}{4}$  inches to  $5\frac{3}{4}$  inches, it is evident that increasing the gutter width increased the tendency for screech. Although no screech was encountered in this investigation with flame holders having gutter widths of  $1\frac{1}{2}$  inches or less, the  $1\frac{1}{2}$ -inch width does not have general significance because screech has been encountered in the short afterburner of figure 21 with gutter widths as small as  $\frac{3}{4}$  inch. However, even in the latter afterburner the screech was much less severe than with the wider gutter flame holders. Although flame-holder blockage varied from 32 to 40 percent of the flow area in this investigation, it is evident that flame-holder width and not blockage was the controlling variable, because several of the nonscreeching flame holders had blockage as high as 39 percent. It is therefore concluded that flame-holder gutter width is an important variable in controlling screech.

#### Increase of Damping Potential

The damping potential of a combustor can be increased by increasing the sound absorption in the combustor and by increasing the interference of pressure waves reflected from various surfaces within the

combustor. These techniques, if carried to the ultimate, will produce an anechoic chamber. Practical design techniques for increasing damping are obvious, and several of these are discussed in the following paragraphs.

Longitudinal fins. - One of several systems investigated as possible damping mechanism was the use of 24 two-inch-wide fins attached to the inner surface of the 32-inch-diameter afterburner shell as shown in figure 25. It was postulated that the longitudinal fins would interfere with the particle motion corresponding to the oscillation modes and thereby possibly eliminate the screech. The use of these fins changed the screech limit and frequency as follows:

|                                     | Screech limit<br>min, f/a | Screech frequency,<br>cps |
|-------------------------------------|---------------------------|---------------------------|
| Operation without longitudinal fins | 0.042                     | 1560                      |
| Operation with longitudinal fins    | .054                      | 1760                      |

Although the acoustic fins materially decreased the screech tendency, screech was not eliminated. Extension of the fins farther downstream, as shown by the dashed lines in figure 25, had no further effect on screech limits.

The change in frequency (from 1560 to 1760 cps) is essentially that which would have been predicted if the duct diameter had been reduced to 28 inches, the diameter of the space within the longitudinal fins.

Another type of longitudinal fin examined consisted of a single plate anchored at the vertex of the cone flame holder and extending downstream of the flame holder. Three modifications were studied in the 26-inch-diameter afterburner. First a single-ring 2-inch-wide gutter flame holder was tested with and without a cylindrical fin extending 9 inches downstream of the flame-holder lip.

The results, shown in figure 26, indicate that the fin was partly successful in eliminating screech. One possible reason for this partial success was thought to be the action of the fin in inhibiting possible vortex interaction in the wake of the flame holder. To examine this possibility the next two modifications were tested.

First a splitter extending 6 inches downstream of a 7-inch diametric flame-holder lip and aligned with the flame holder was tested in the 26-inch-diameter afterburner. The screech tendency was observed to be only slightly less with this splitter than without.

To this configuration was added a second splitter perpendicular to the first, oriented along the combustor center line, and extending 9 inches downstream of the flame holder. This change caused a marked reduction in screech tendency.

It was concluded from these tests that such fins alter the screech tendency by acoustic interference.

Tapered burner. - It was felt that a tapered burner might eliminate screech since it was not apparent that a simple resonance, such as has been described for cylinders, could exist in such a configuration. Consequently, a burner 45 inches long was constructed with the diameter tapering from 26 inches at the inlet to 18.6 inches at the exit. This was the maximum taper believed practical. When the burner was tested in the 26-inch duct rig, no difference in screech tendency was observed over that of a straight-walled burner. These results are not too surprising, since a straight-walled burner will screech well even though the natural frequency at the inlet is different from that at the exit because of the temperature rise through the burner.

Perforated liner. - A perforated liner was designed for maximum acoustic damping and was installed in the same afterburner (fig. 25) used to investigate the longitudinal fins. The construction details of the perforated liner are shown in figure 27(a) and a photograph of the liner installed in the afterburner is shown in figure 27(b). The use of this liner completely eliminated screech with the 2-ring  $\frac{3}{4}$ -inch-wide V-gutter flame holder. Inasmuch as larger gutter widths were shown to increase the tendency to screech, a single-ring,  $1\frac{1}{2}$ -inch-wide gutter flame holder and a single-ring 3-inch-wide V-gutter flame holder were investigated in turn with the perforated liner. Screech could not be obtained at any fuel-air ratio with either of the larger flame holders. Further attempts to force screech with the perforated liner included the introduction of large variations in both radial and circumferential fuel distribution. Screech could not be produced with the perforated liner. This result was felt to be particularly significant since the screech tendencies of this afterburner liner were very strong.

Additional investigations were then conducted with a 19-inch length of perforated liner in the 26-inch duct burner (fig. 28). The results of this investigation are shown in figure 29. Without the perforated liner the burner screeched at all conditions investigated. Using the 19-inch long perforated liner eliminated screech at a burner-inlet pressure of 1400 pounds per square inch and although screech was encountered at fuel-air ratios from 0.05 to 0.08, it was not severe. The addition of another 10 inches of liner (29-in. length) completely eliminated the screech at a burner-inlet pressure of 1750 pounds per square inch. In addition, the burner operated at about 2200 pounds per square foot without screech at any fuel-air ratio.

The use of the perforated liner to increase the damping potential of the burner has been by far the most effective mechanism for control of screech that has been investigated at the Lewis laboratory. The length of liner required will undoubtedly vary with peak gas velocity and combustion rate in the burner. The liner should enclose the region of maximum heat release, as this is the region of greatest driving potential.

The perforated liner of figure 27 also served as a cooling liner with the relatively cool turbine-discharge gases flowing between the liner and the afterburner shell. The liner was quite effective in eliminating hot spots on the afterburner shell. The perforated liner from the cooled installation was essentially free of buckling and warping, whereas the liner of figure 28, which was not cooled, was badly buckled after a relatively few hours of operation.

Two perforated or louvered cooling liners (figs. 30 and 31) which have also served as acoustic dampers have recently been investigated. These liners were installed in a 32-inch-diameter afterburner and were operated over a range of burner-inlet total pressures from 670 to 3100 pounds per square foot and fuel-air ratios as high as 0.062 without encountering screech at any of the conditions investigated. A large number of flame-holder and fuel-injection system variables were included in these operations (refs. 16 to 18).

#### OTHER COMBUSTION INSTABILITY PHENOMENA

Although the present paper is intended to summarize some of the aspects of screech, a brief mention of other combustion instability problems is in order. In afterburners and ram-jet combustors, other forms of combustion instability encountered have been referred to as "rumble" and "buzz."

Rumble. - The type of combustion instability referred to as rumble is usually caused by explosions of large pockets of combustible mixture. This violent instability usually occurs at frequencies of one to a few cycles per second, and generally occurs only for a few cycles at ignition of the burner or near either rich or lean blow-out. During starts, observations through windows in the burner shell indicated that the rumble is due to flash back into the fuel-mixing zone upstream of the flame holder; near the blow-out limits it is probably caused by the blow-out and reignition of local pockets of fuel-air mixture, at or downstream of the flame holder, that momentarily exceed the combustible limits of fuel-air ratio (see ref. 7).

Buzzing. - Buzzing is a term used to denote combustion which produces pressure pulsations of intermediate frequency on the order of perhaps 10 to 50 cycles per second. High-speed schlieren motion pictures of a two-dimensional ram-jet model with transparent walls have provided an explanation of this type of instability as follows:

(1) Upon ignition, a flame front fans out from each flame stabilizer and intersects either a wall or the flame front from the adjacent flame stabilizer at a point some distance downstream.

(2) A curved flame front starts at the point of intersection and travels upstream with increasing velocity through the wedge-shaped pocket of combustibles bounded by the intersecting flame fronts.

(3) The curved flame front progresses to a point somewhat upstream of the flame holder whereupon combustion ceases as the flame front reaches an unconditioned fuel-air mixture. The pressure pulse produced by this curved flame front momentarily stops or reverses the direction of flow of the gas column.

(4) Following dissipation of the pressure pulse, the flow is re-established and a fresh charge of combustible mixture displaces the burner charge, whereupon ignition occurs and the cycle repeats.

Rumble, buzz, and screech are each different phenomena and are characterized by low, low-to-intermediate, and high-frequency oscillations. Each can be severe enough to cause engine damage but the very high-energy dissipation from the high-frequency oscillations has been the greatest offender in combustion studies at the NACA Lewis laboratory.

Combustion instability has also been experienced in rocket engines. Rocket engine combustion instabilities have been attributed to either "chugging" or "screaming" (refs. 9, 19, and 20).

Chugging. - Chugging is a hydrodynamic coupling between combustion-chamber pressure and feed line flow and produces a pulsing operation. Chugging is characterized by relatively low frequencies, 20 to 200 cycles per second.

Screaming. - Screaming, however, is characterized by relatively high frequencies, up to 10,000 cycles per second, and is similar in its other characteristics to screech. Recent research on rocket screaming at the Lewis laboratory has identified transverse oscillations in a rocket motor which exist concurrently and independently of the longitudinal mode of vibration. Rocket screaming frequencies, however, have generally been correlated with the closed-closed pipe organ or longitudinal mode of oscillation. With the small rockets in use in many investigations, the frequency of a transverse mode of oscillation would

be too high to measure with the instrumentation usually employed. However, the presence of transverse oscillation in rocket engines has been described in reference 9 and these oscillations have also been identified during recent studies of screaming rockets at the Lewis laboratory. These oscillations are observed to spin, as did those discussed in reference 9.

### CONCLUDING REMARKS

The present studies have shown that screech is characterized by resonant acoustic oscillation in a transverse mode in afterburners so far investigated. The energy for driving this oscillation is possibly derived from the combustion process although the possibility that some energy may be supplied by the kinetic energy of the stream cannot be ignored. Various schemes for eliminating or controlling screech by reducing the driving potential have proved marginal, their utility varying from one configuration to the next. On the other hand, a perforated liner in the combustion chamber eliminated screech entirely in all the configurations tested, including burners which screeched very severely without the liner. These studies strongly indicate that such a liner will serve as a satisfactory screech-control device in any burner.

Since the amount of damping can be varied by varying the length of the perforated liner downstream of the flame holder, it might be possible to establish a screech of controlled amplitude in the combustion chamber. A thorough quantitative investigation of this control technique is required to determine the extent to which possible beneficial effects of screech, such as increased combustion efficiency, can be utilized without producing destructive oscillations.

Lewis Flight Propulsion Laboratory  
National Advisory Committee for Aeronautics  
Cleveland, Ohio, February 8, 1954

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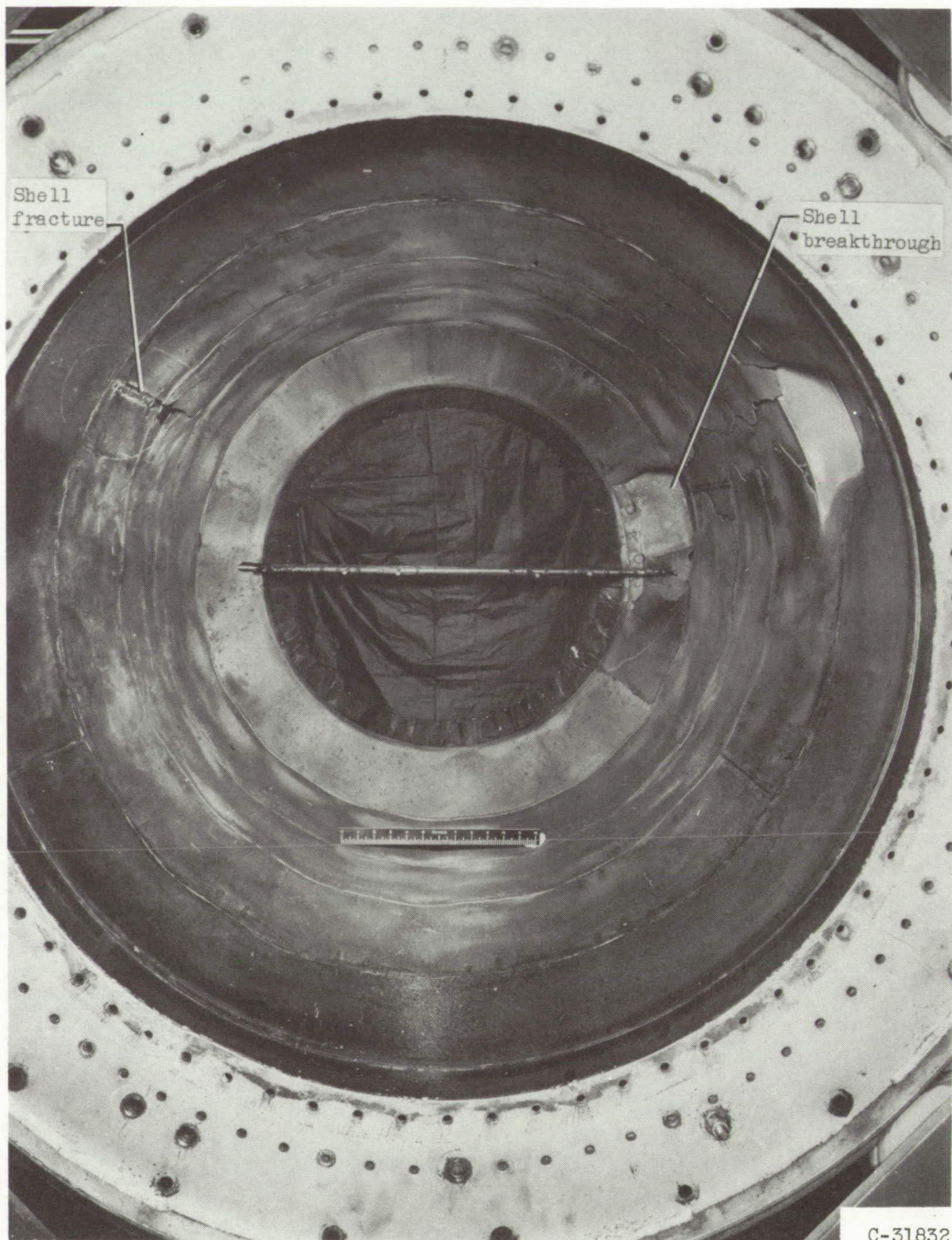


Figure 1. - Example of screech-produced afterburner shell failure.

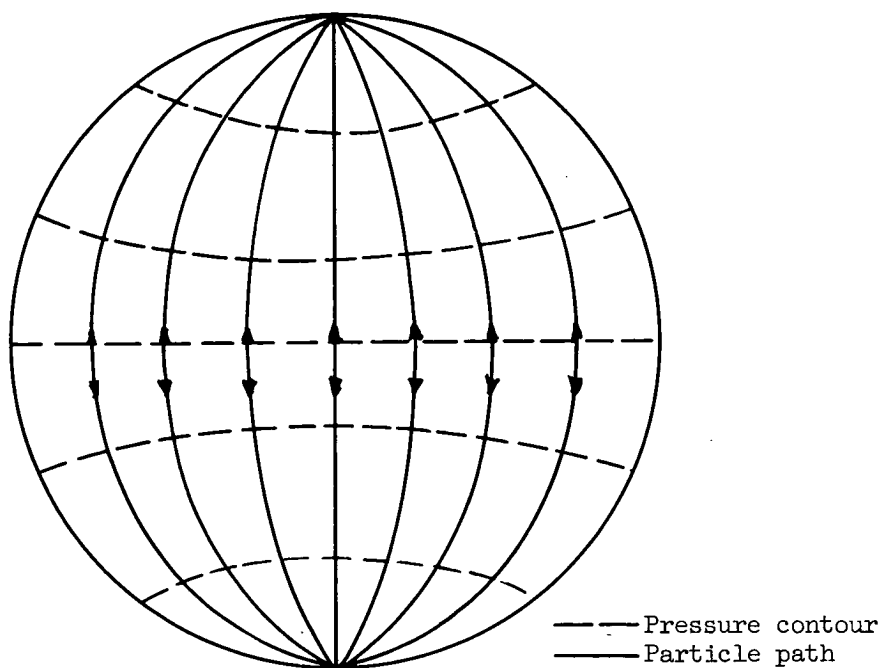


Figure 2. - Loci of particle paths and pressures for first transverse mode (1,0).

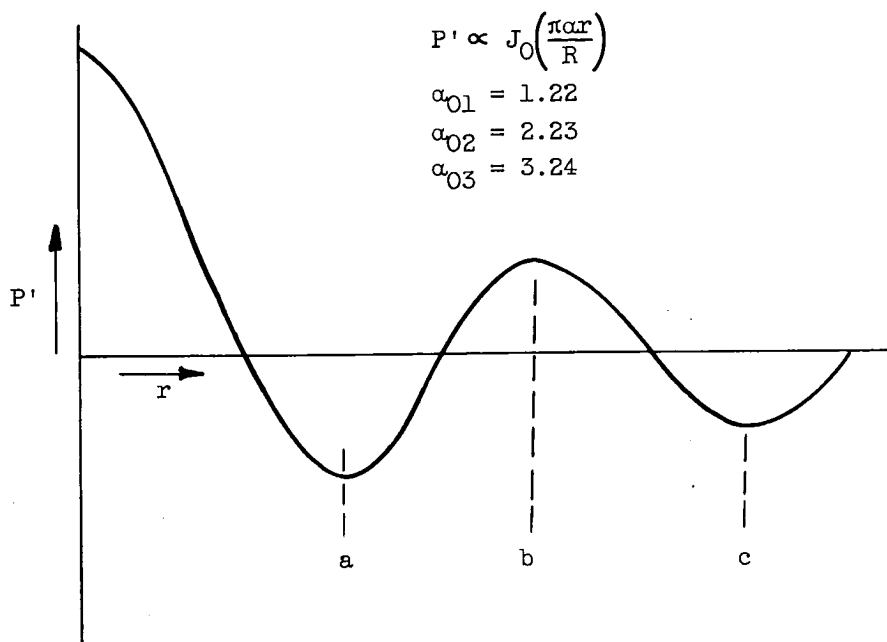
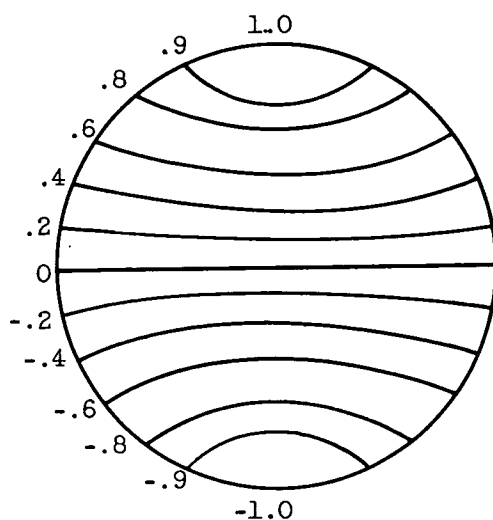


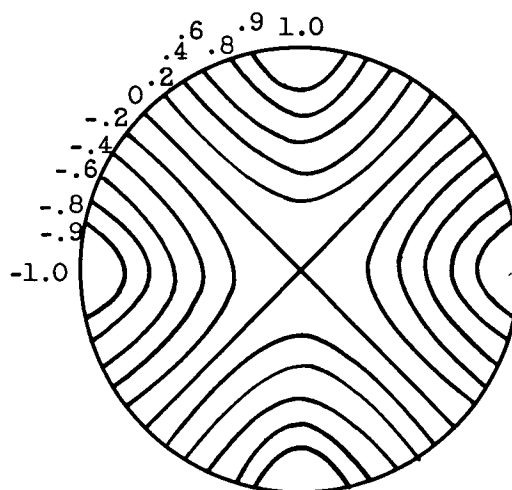
Figure 3. - Variation of pressure with radius for radial mode.



$$n = 1$$

$$\alpha = 0.586$$

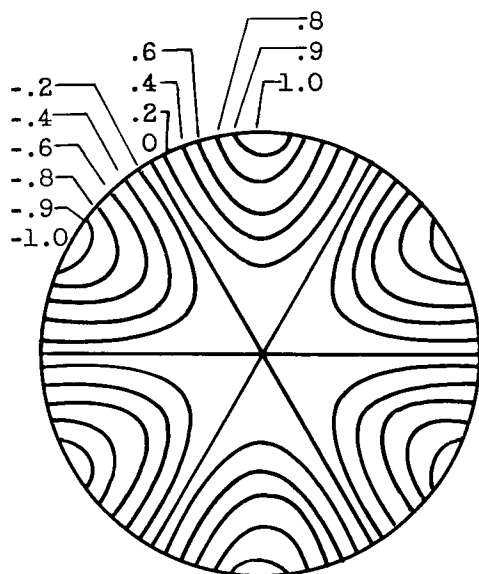
$$P' \propto J_1\left(\frac{\pi \alpha r}{R}\right) \cos \theta$$



$$n = 2$$

$$\alpha = 0.982$$

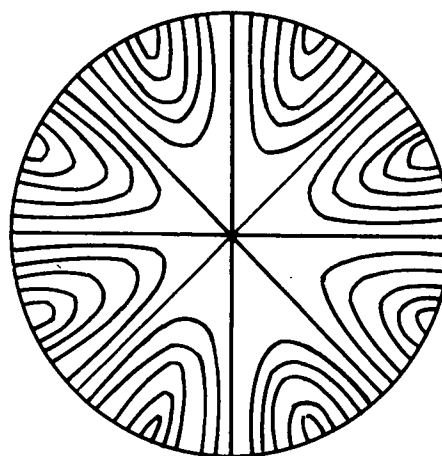
$$P' \propto J_2\left(\frac{\alpha \pi r}{R}\right) \cos 2\theta$$



$$n = 3$$

$$\alpha = 1.34$$

$$P \propto J_3\left(\frac{\pi \alpha r}{R}\right) \cos 3\theta$$



$$n = 4$$

$$\alpha = 1.70$$

$$P \propto J_4\left(\frac{\alpha \pi r}{R}\right) \cos 4\theta$$

(a)  $m = 0$ .

Figure 4. - Pressure contours for various transverse modes.

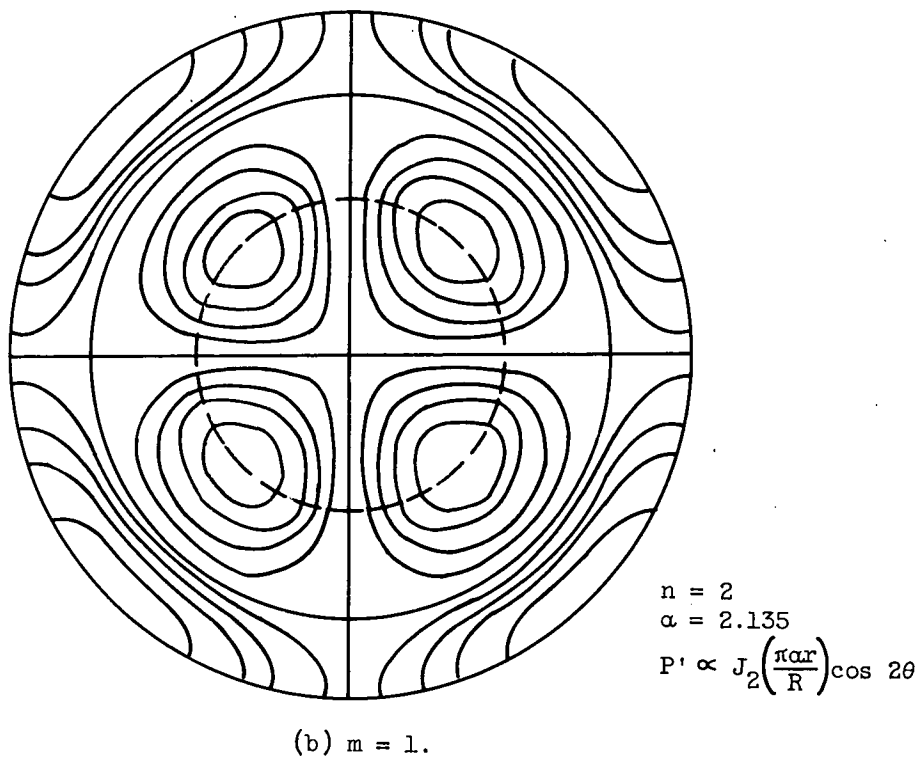
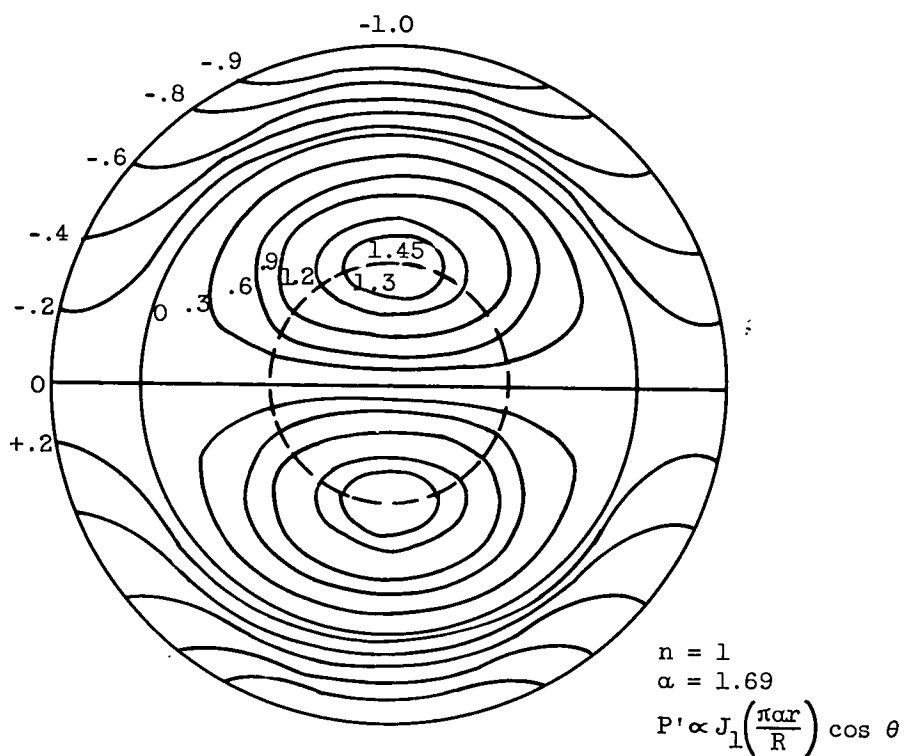
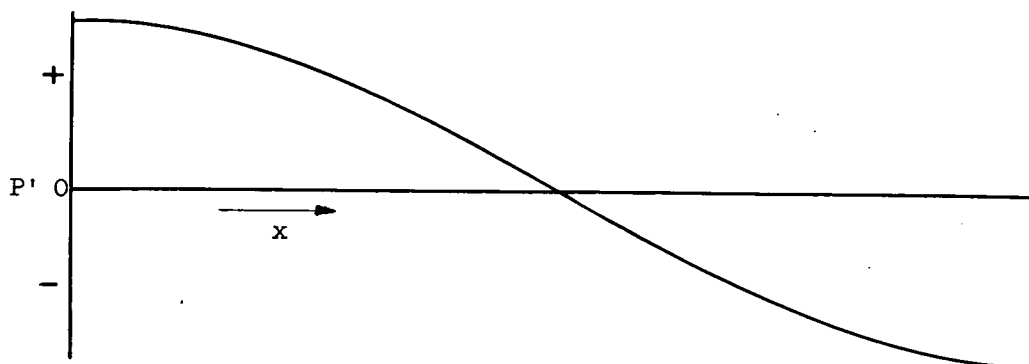
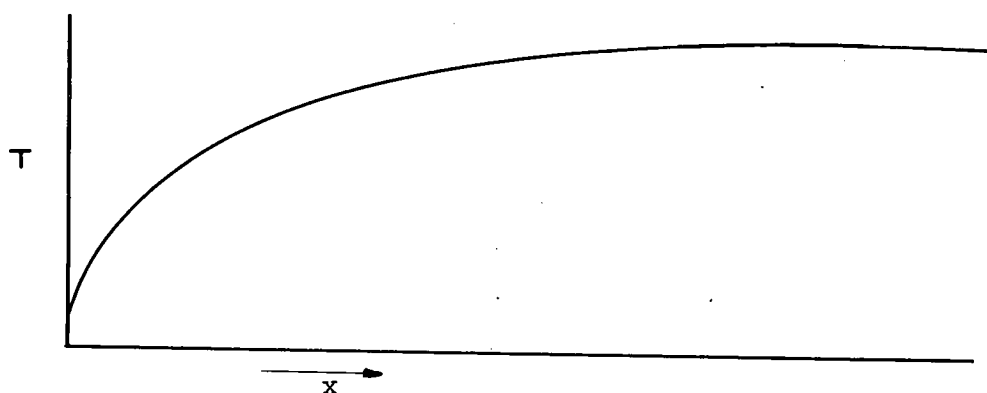


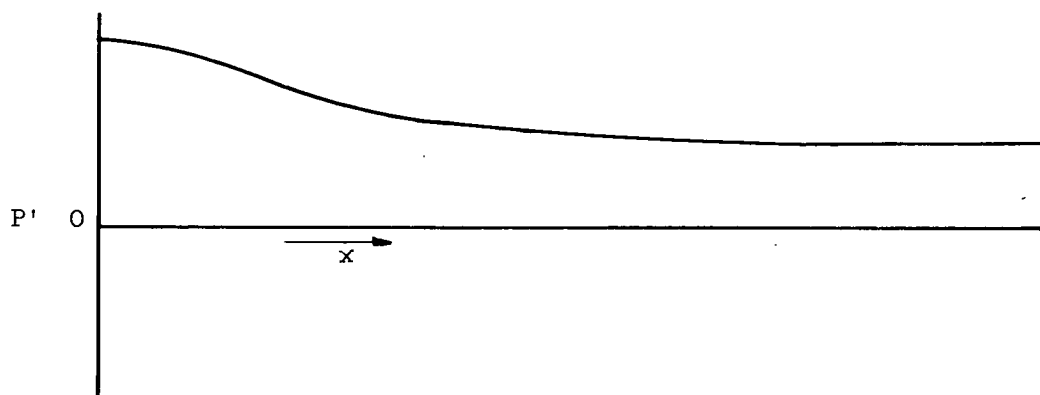
Figure 4. - Concluded. Pressure contours for various transverse modes.



(a) Pressure amplitude for pure longitudinal wave.



(b) Typical temperature distribution.



(c) Pressure variation due to temperature variation of figure 5(b).

Figure 5. - Two types of longitudinal pressure variation.

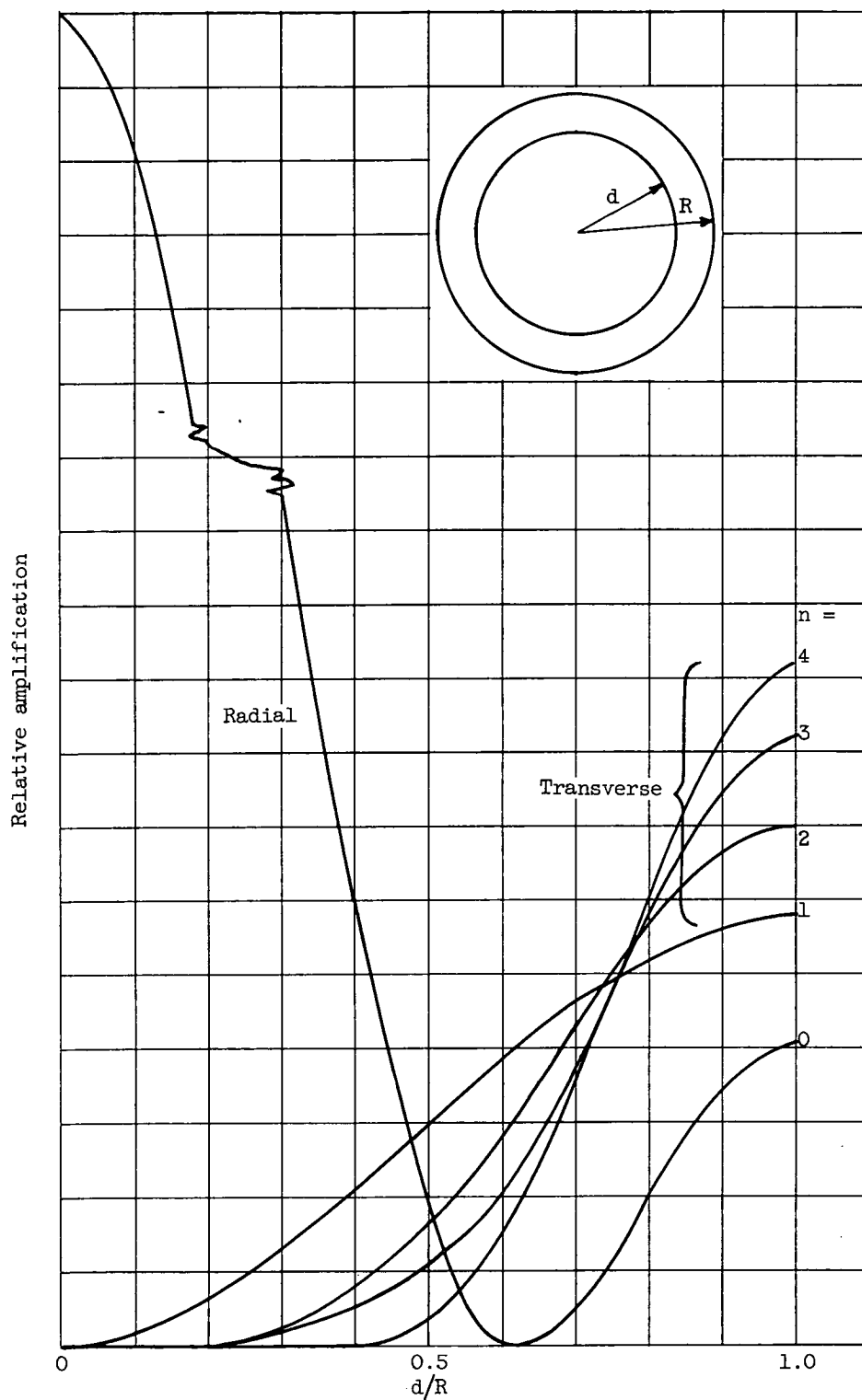


Figure 6. - Relative amplification for several modes (no center-body).



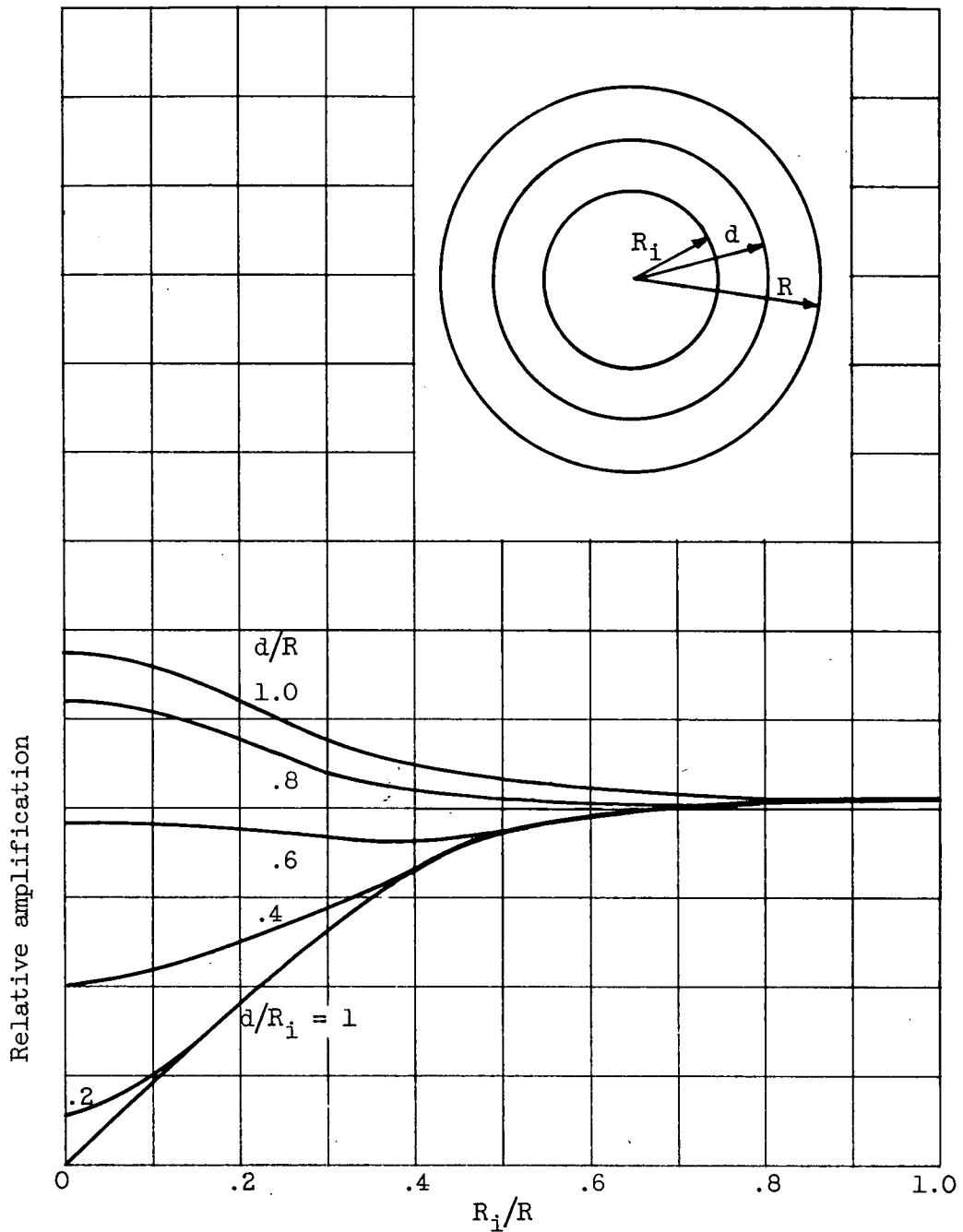


Figure 7. - Relative amplification versus centerbody diameter for first transverse mode (1,0).

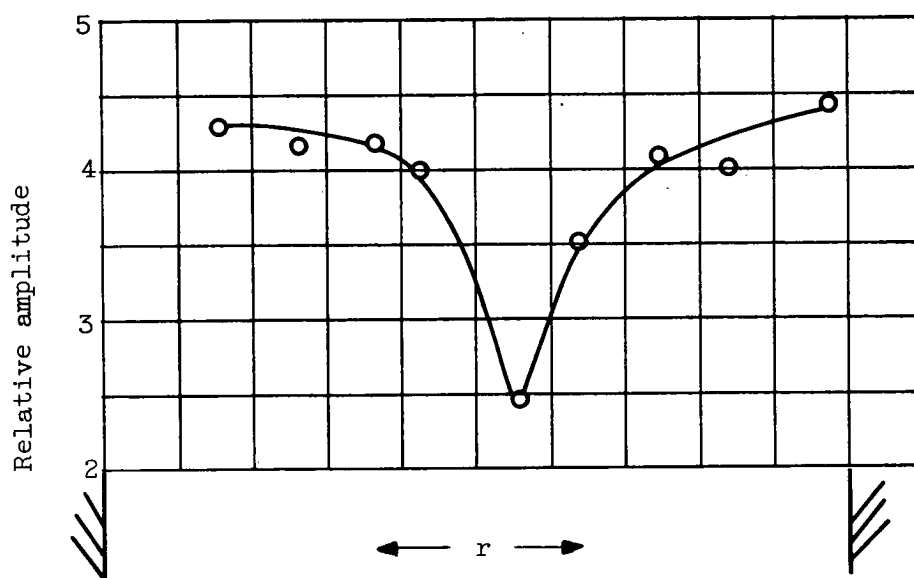


Figure 8. - Amplitude profile across 6-inch burner.

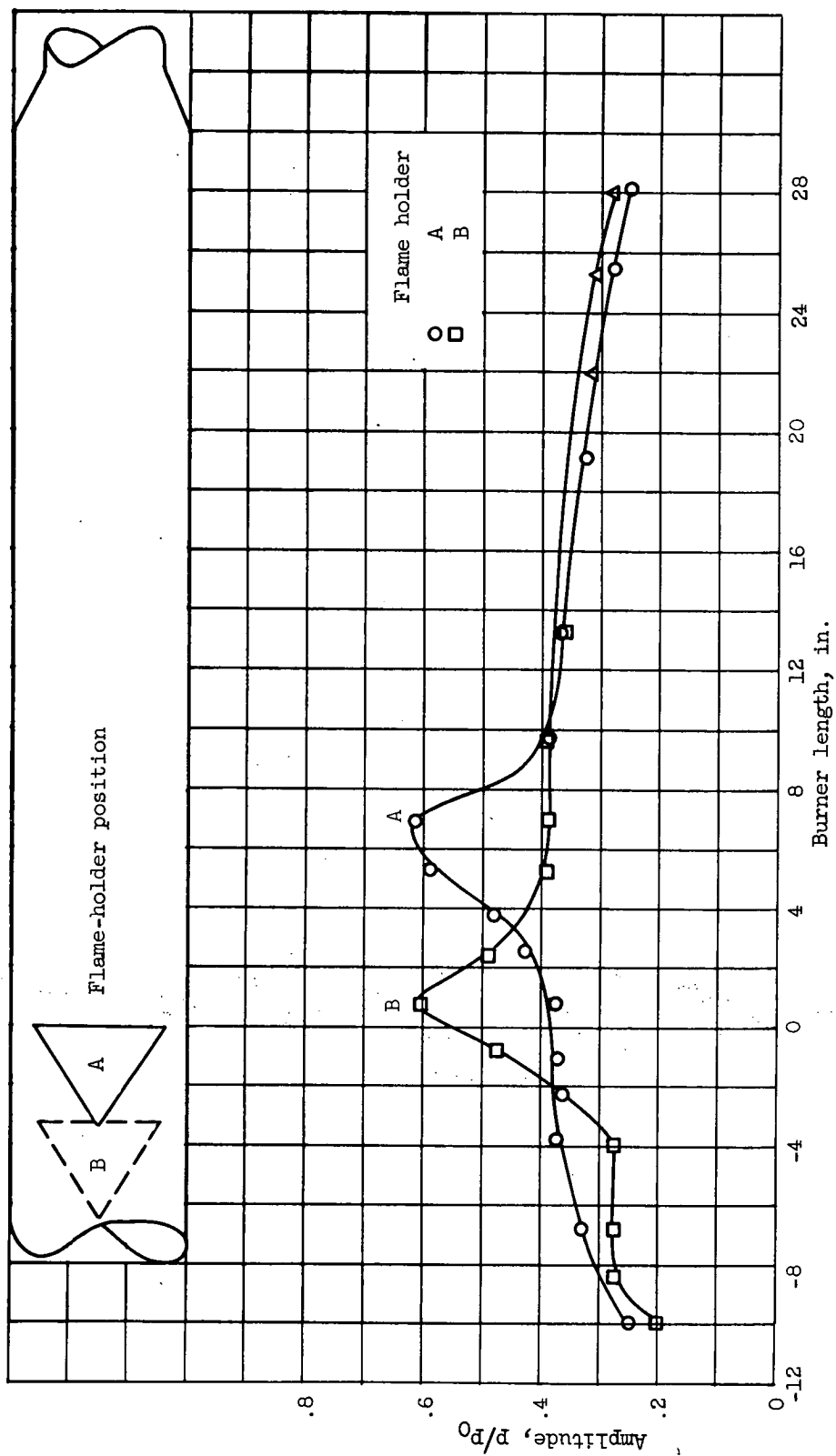


Figure 9. - Amplitude distribution for two flame-holder positions in 6-inch burner.

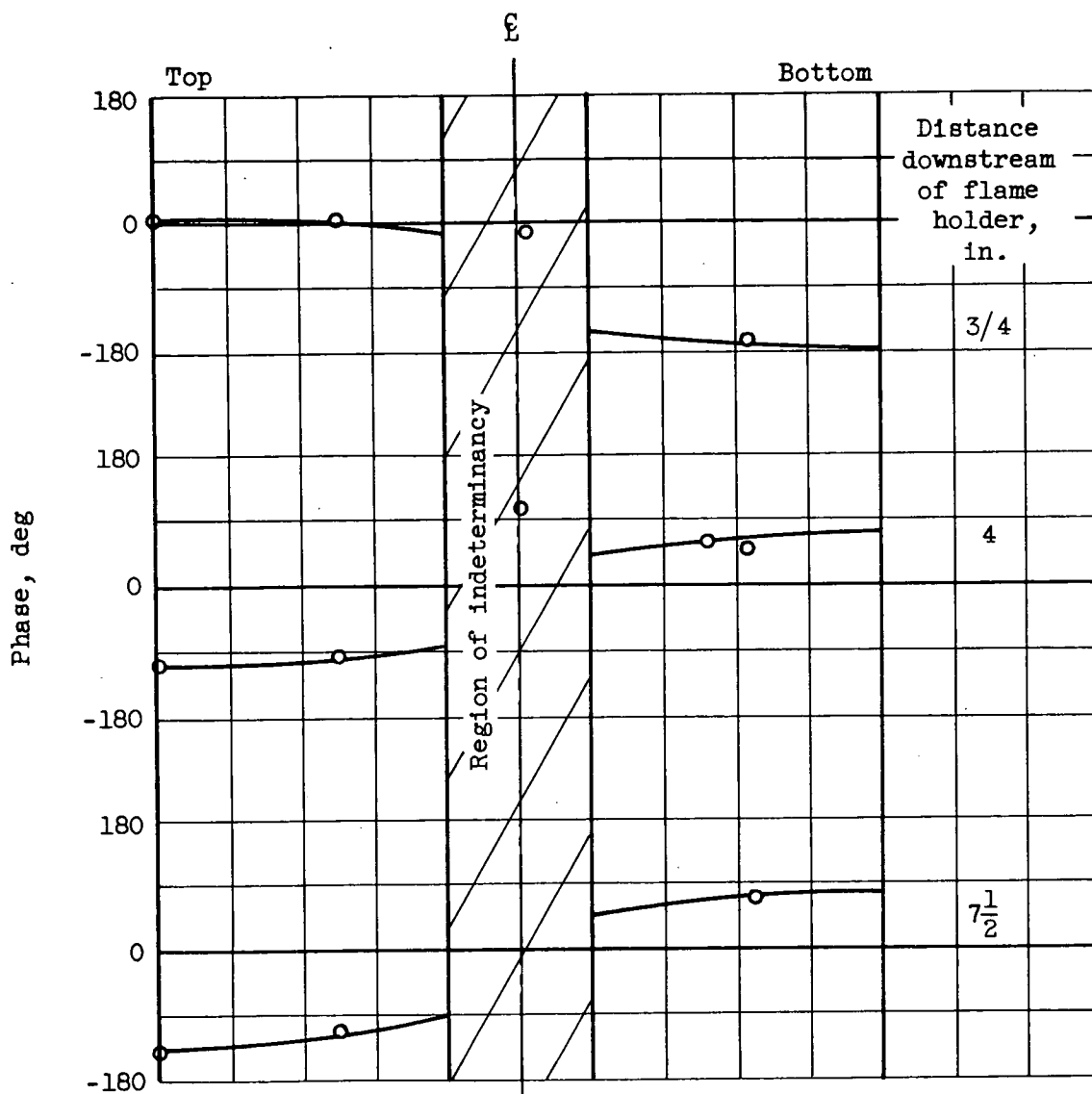


Figure 10. - Phase of pressure signal relative to signal at top of burner  $3/4$  inch downstream of flame holder for three flame-holder positions.

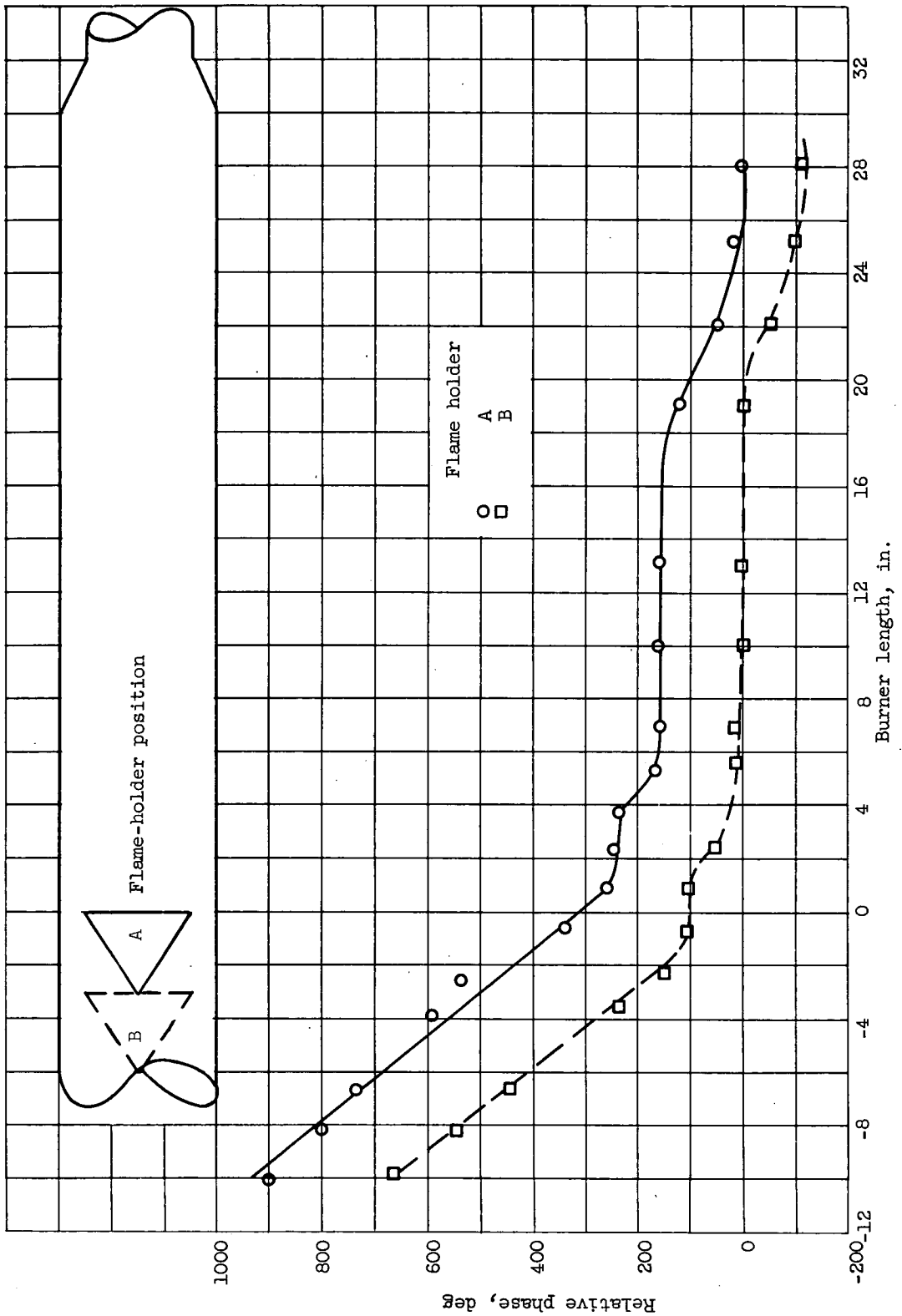
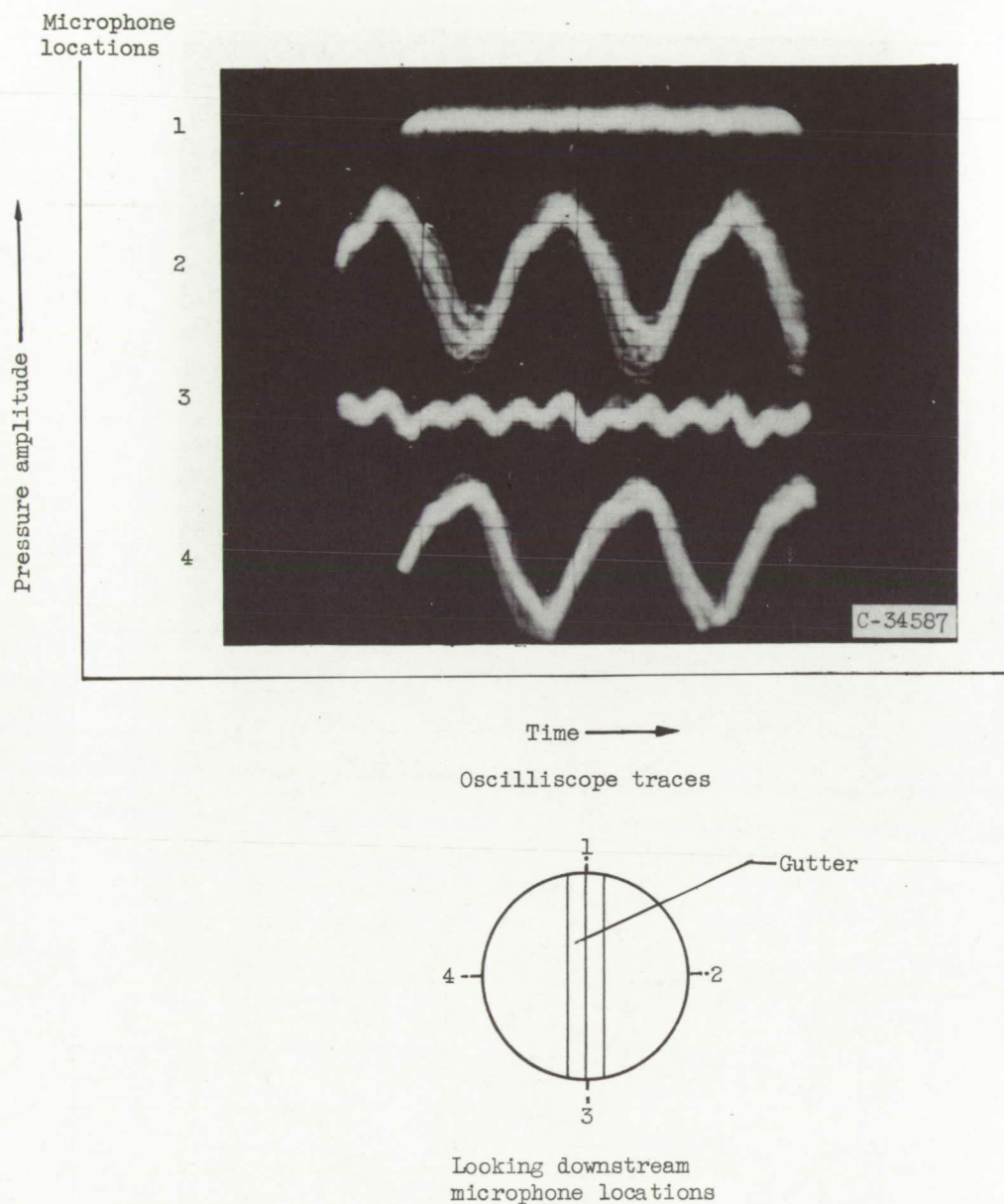
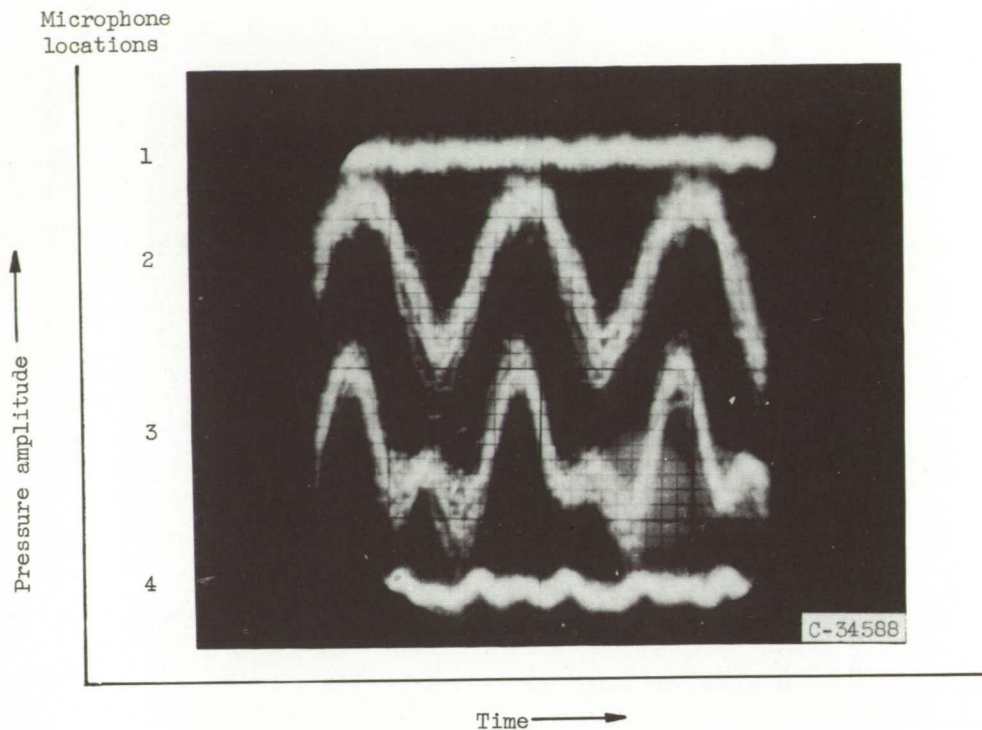


Figure 11. - Phase distribution for two flame-holder positions in 6-inch burner.

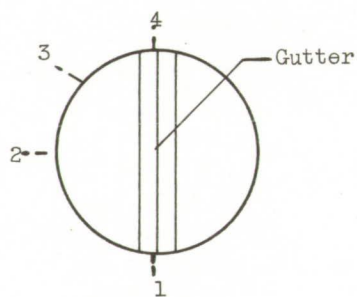


(a) Microphones equally spaced; location of microphone taps, 1.0 inch downstream of flame holder; flame-holder width, 8 inches; screech frequency, 650 cycles per second.

Figure 12. - Phase relations of screech oscillations in 26-inch-diameter burner with diametrical V-gutter flame holder.

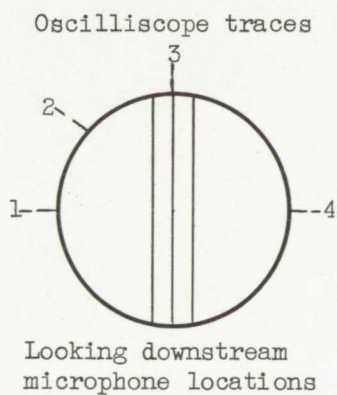
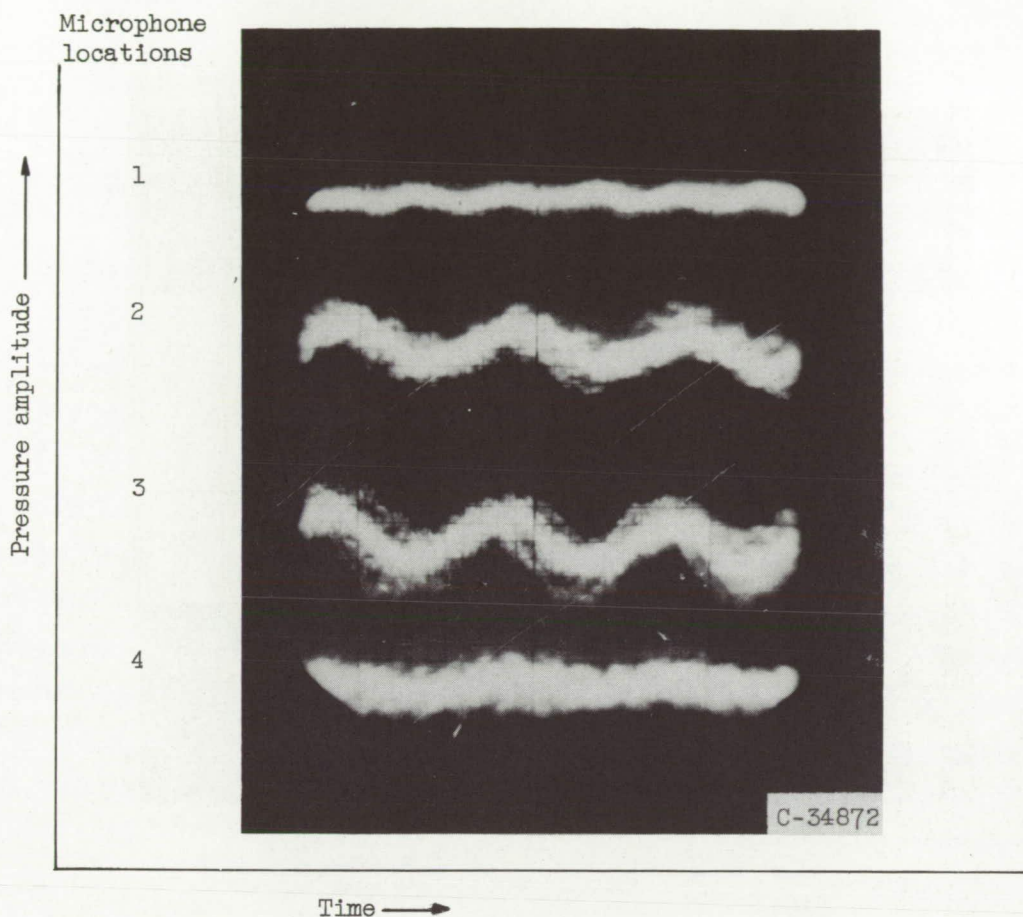


Oscilloscope traces

Looking downstream  
microphone locations

(b) Microphones unequally spaced; location of microphone taps, 1.0 inch downstream of flame holder; flame-holder width, 8 inches; screech frequency, 650 cycles per second.

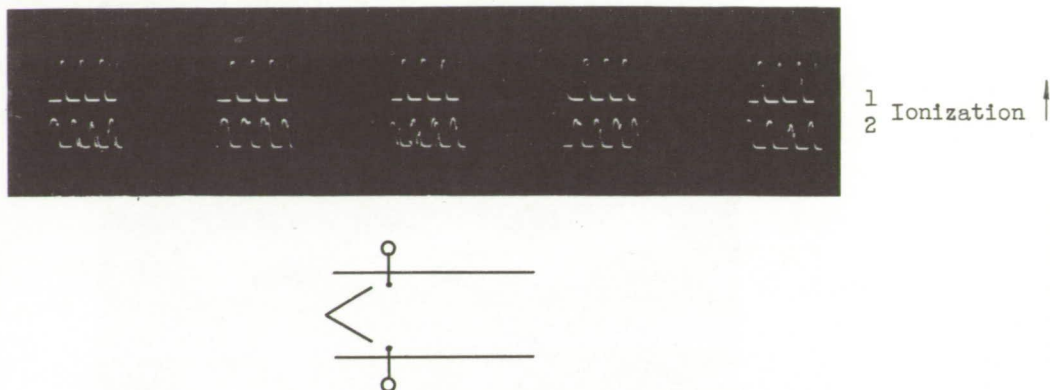
Figure 12. - Continued. Phase relations of screech oscillations in 26-inch-diameter burner with diametrical V-gutter flame holder.



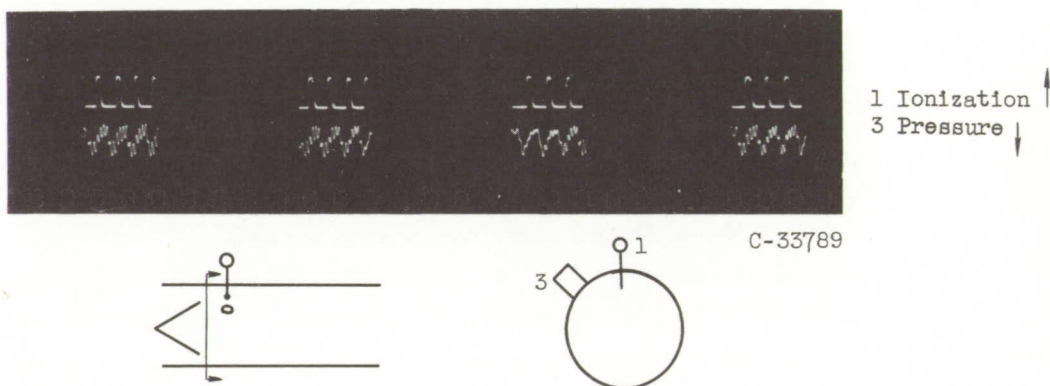
(c) Microphones unequally spaced; location of microphone taps, 5.2 inches downstream of flame holder; flame-holder width, 5 inches; screech frequency, 550 cycles per second.

Figure 12. - Concluded. Phase relations of screech oscillations in 26-inch-diameter burner with diametrical V-gutter flame holder.





(a) Ionization traces top and bottom of burner  $3/4$  inch from wall.



(b) Ionization and pressure traces top and  $60^\circ$  from top, respectively.

Figure 13. - Ionization and pressure traces  $3/4$  inch downstream of flame holder in 6-inch burner.

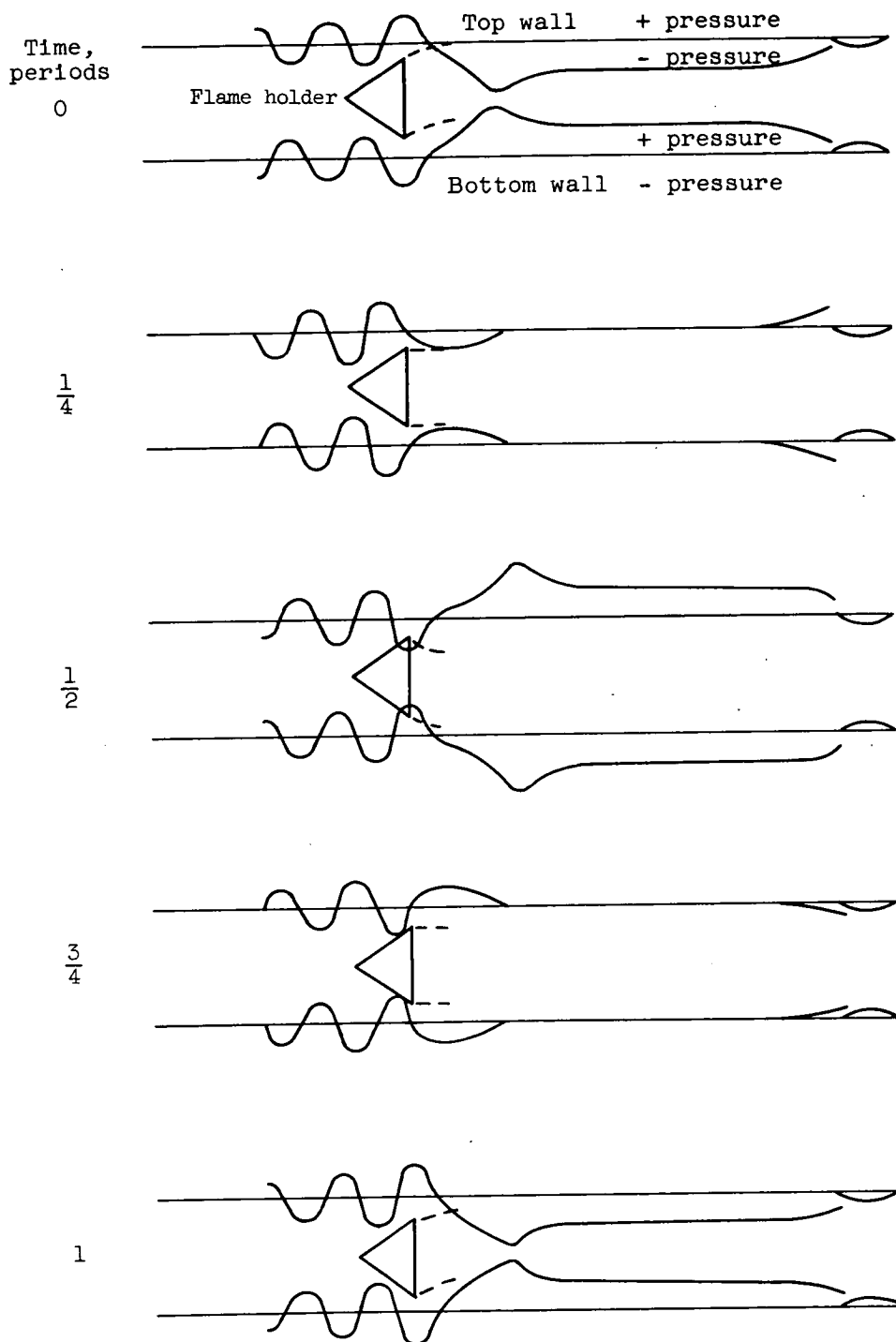


Figure 14. - Reconstruction of pressure and flame displacement sequence.

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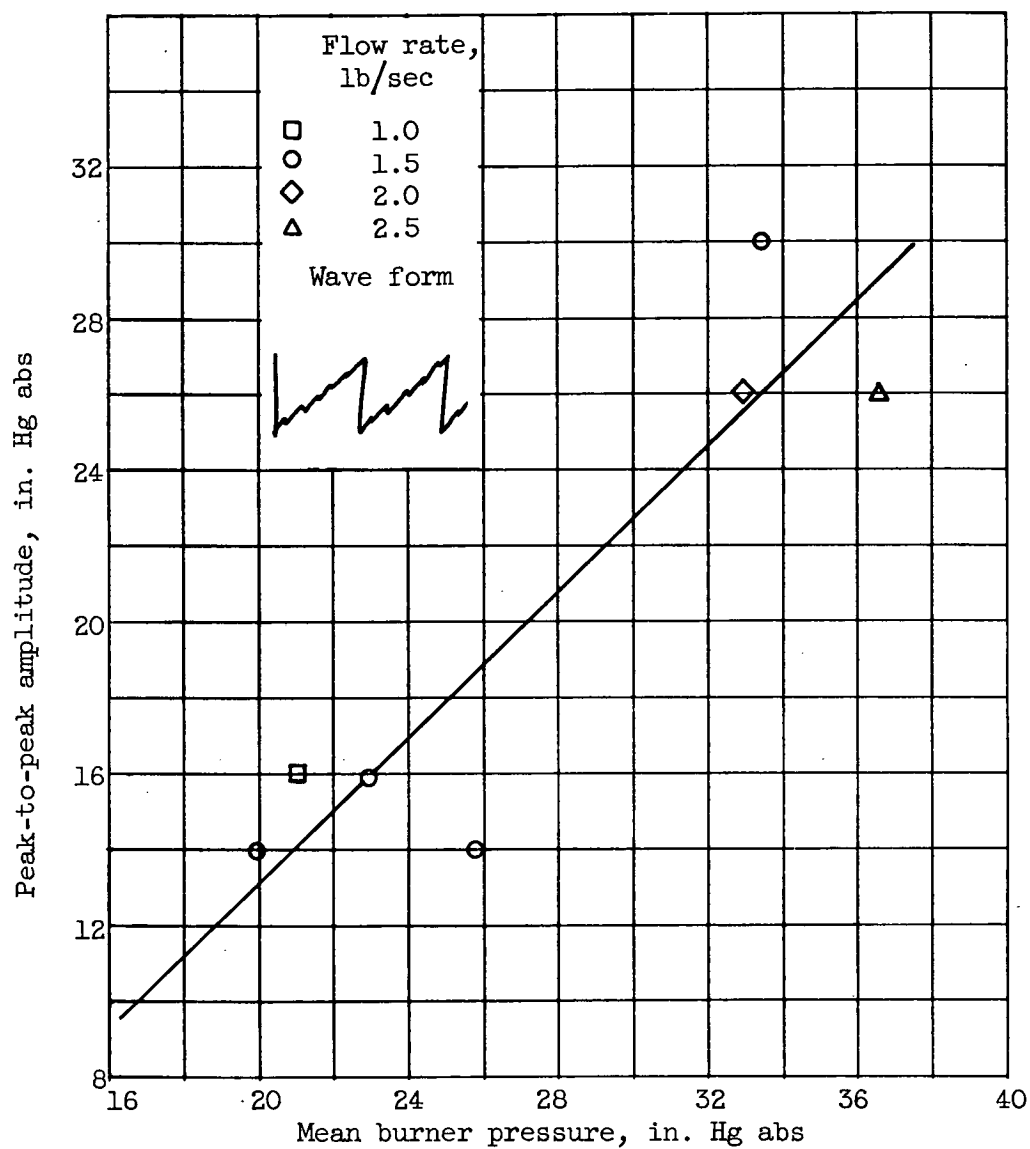


Figure 15. - Peak-to-peak screech amplitudes measured  $5\frac{1}{4}$  inches upstream of flame holder for four different flow rates.

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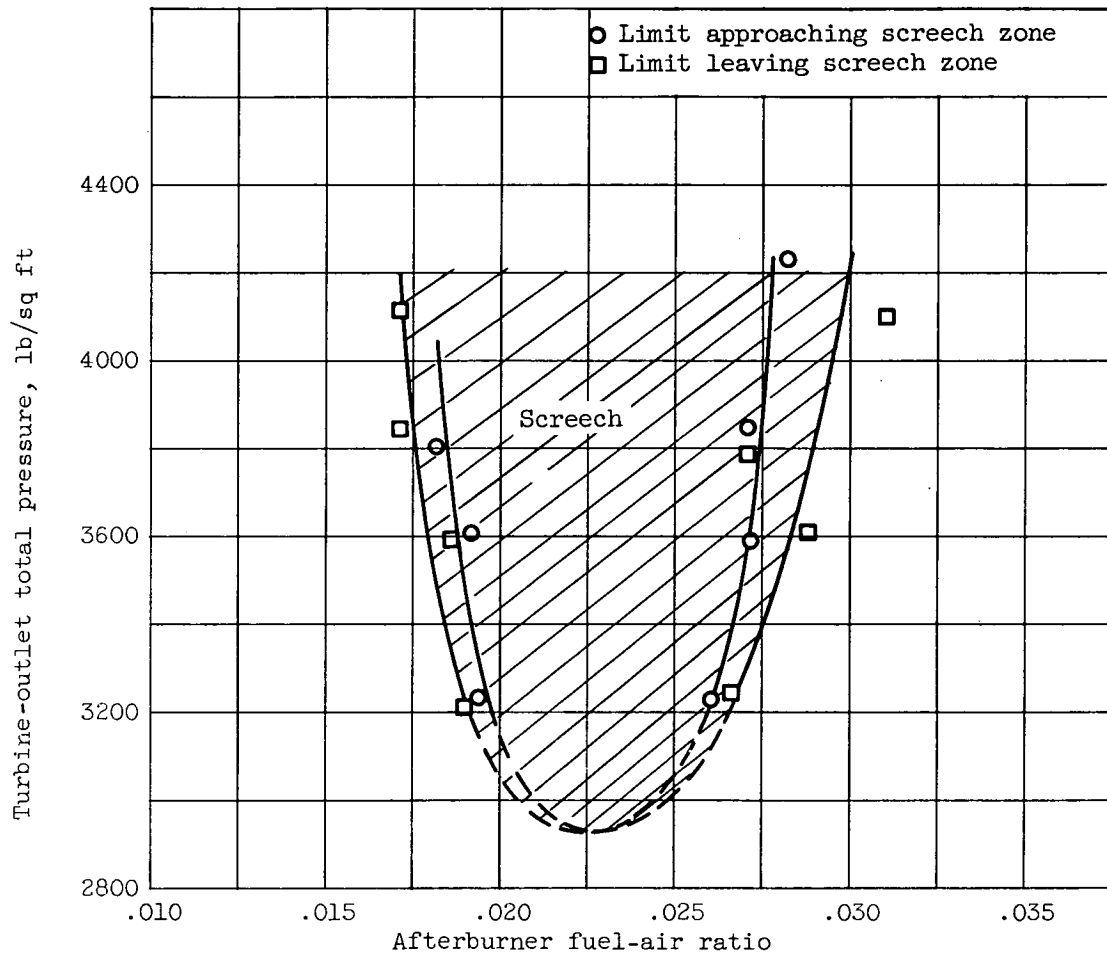
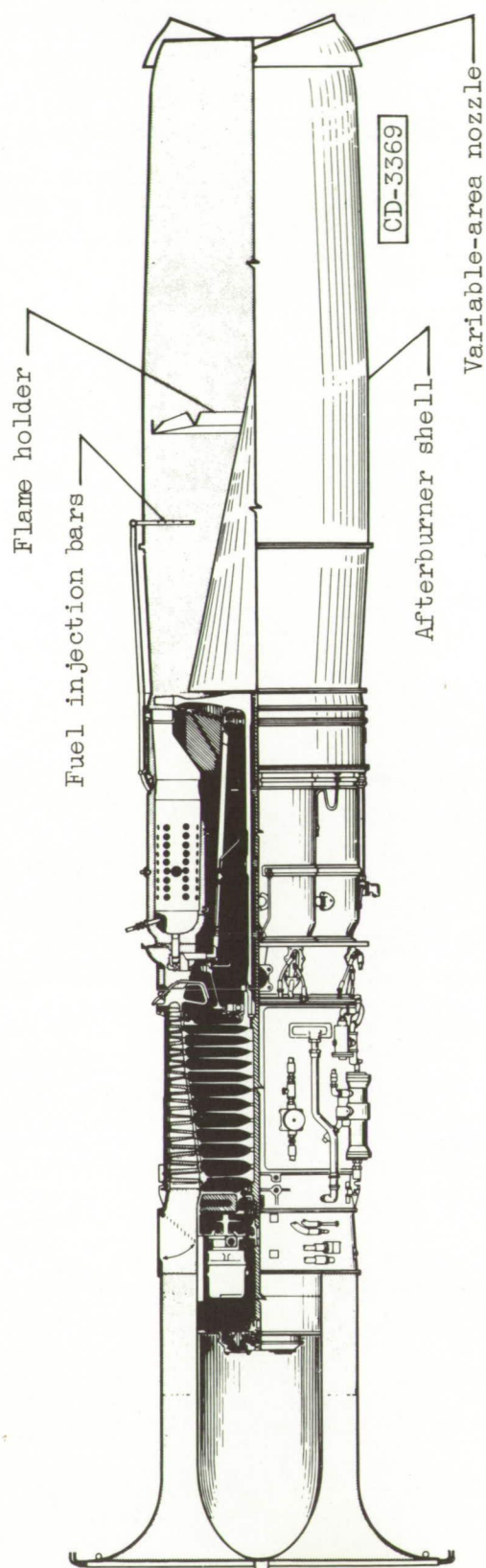
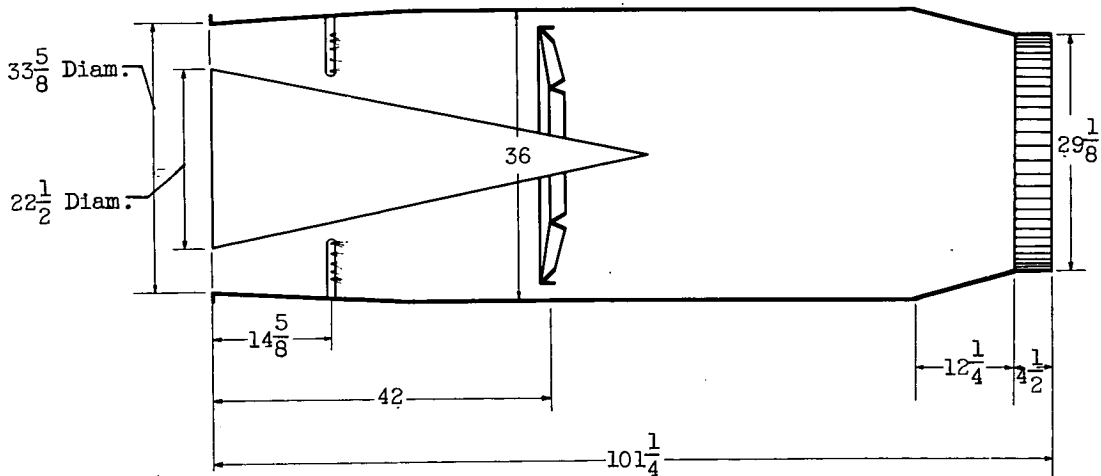


Figure 16. - Variation of screech limits with afterburner-inlet total pressure for 36-inch-diameter afterburner. Afterburner-inlet temperature, 1685° R.

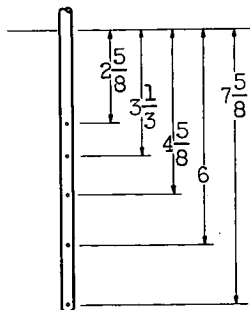


(a) Afterburner mounted on turbojet engine showing primary components.

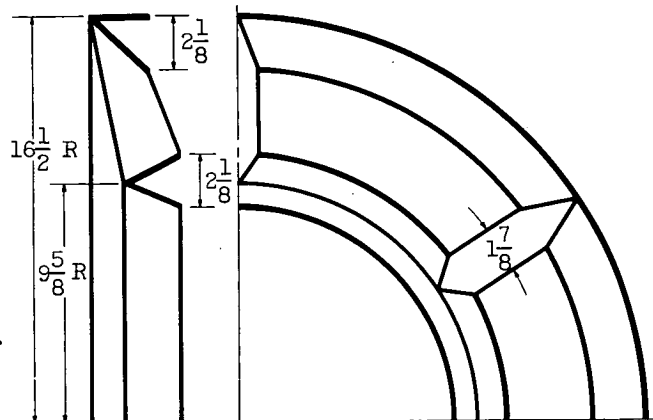
Figure 17. - Construction details of afterburner configuration A.  
(All dimensions are in inches.)



(b) Location of afterburner components.



Orifice area 0.00754 sq in.  
 Orifice diam. 0.031 in.  
 Number of bars 20



CD-3370

Blocked area, 357.5 sq in. = 35 percent blockage

(c) Fuel-injection bars.

(d) Flame holder.

Figure 17. - Concluded. Construction details of afterburner configuration A.  
 (All dimensions are in inches.)

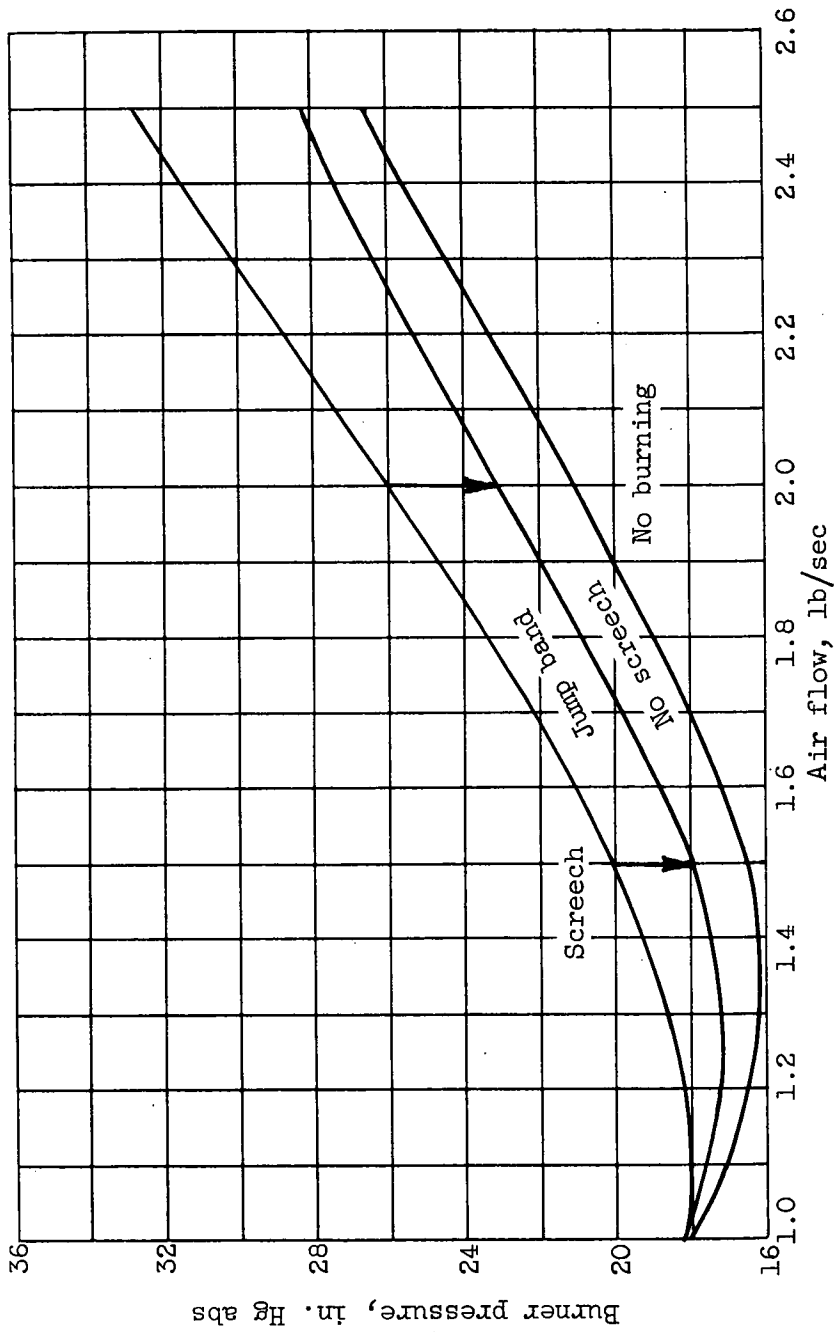


Figure 18. - Lower pressure limits for screech and burning at four mass flows. Equivalence ratio, 1.

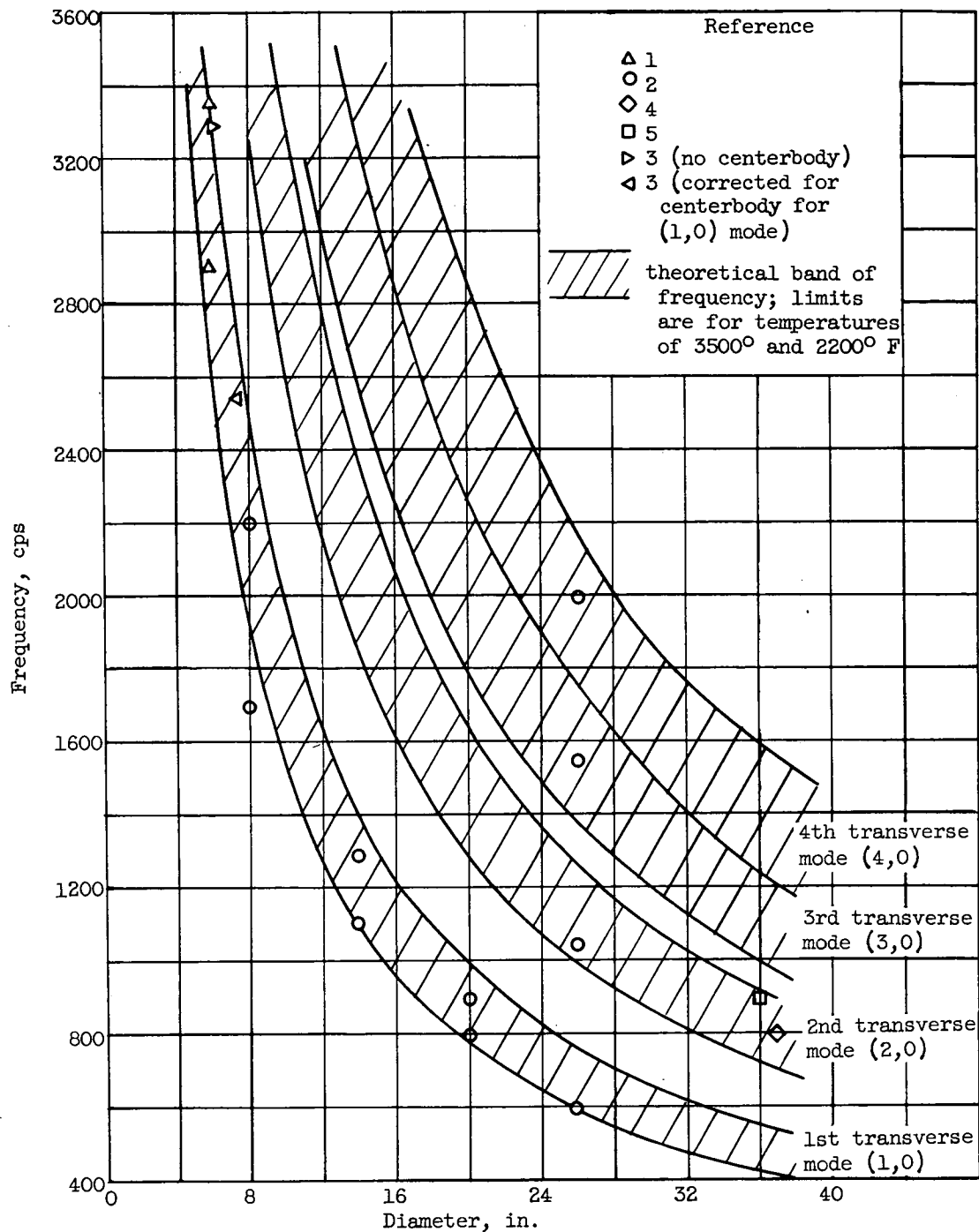
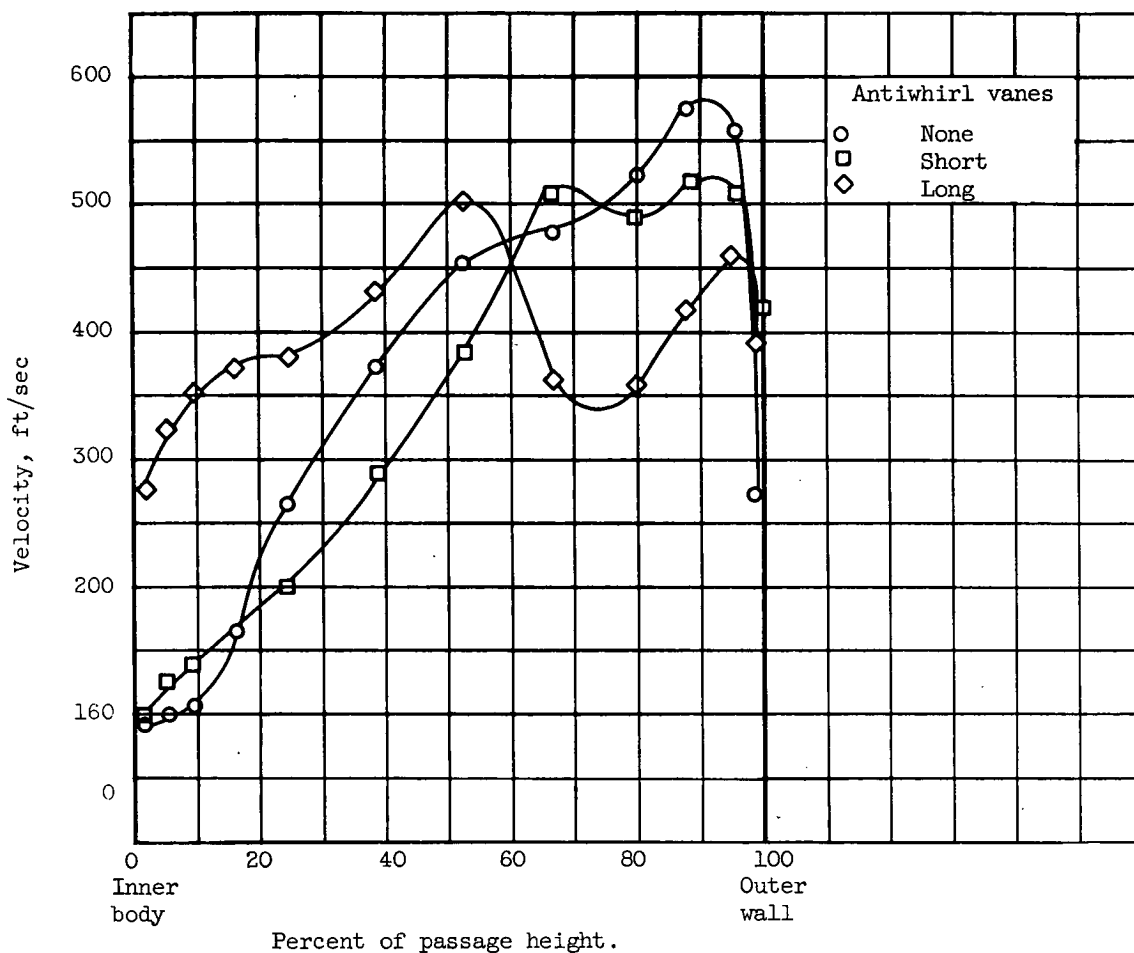
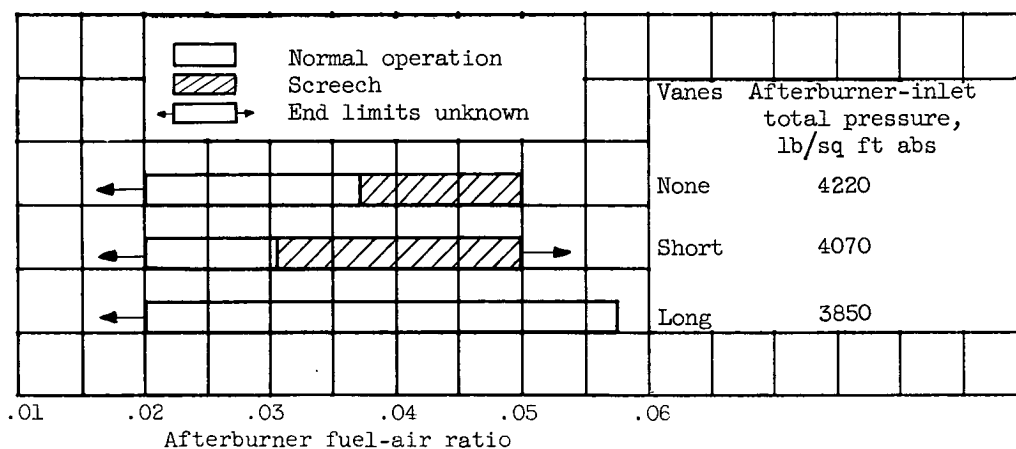


Figure 19. - Variation of frequency with burner diameter.





(a) Diffuser-exit velocity profile.



(b) Screech limits.

Figure 20. - Effect of antiwhirl vanes on performance of afterburner configuration A.

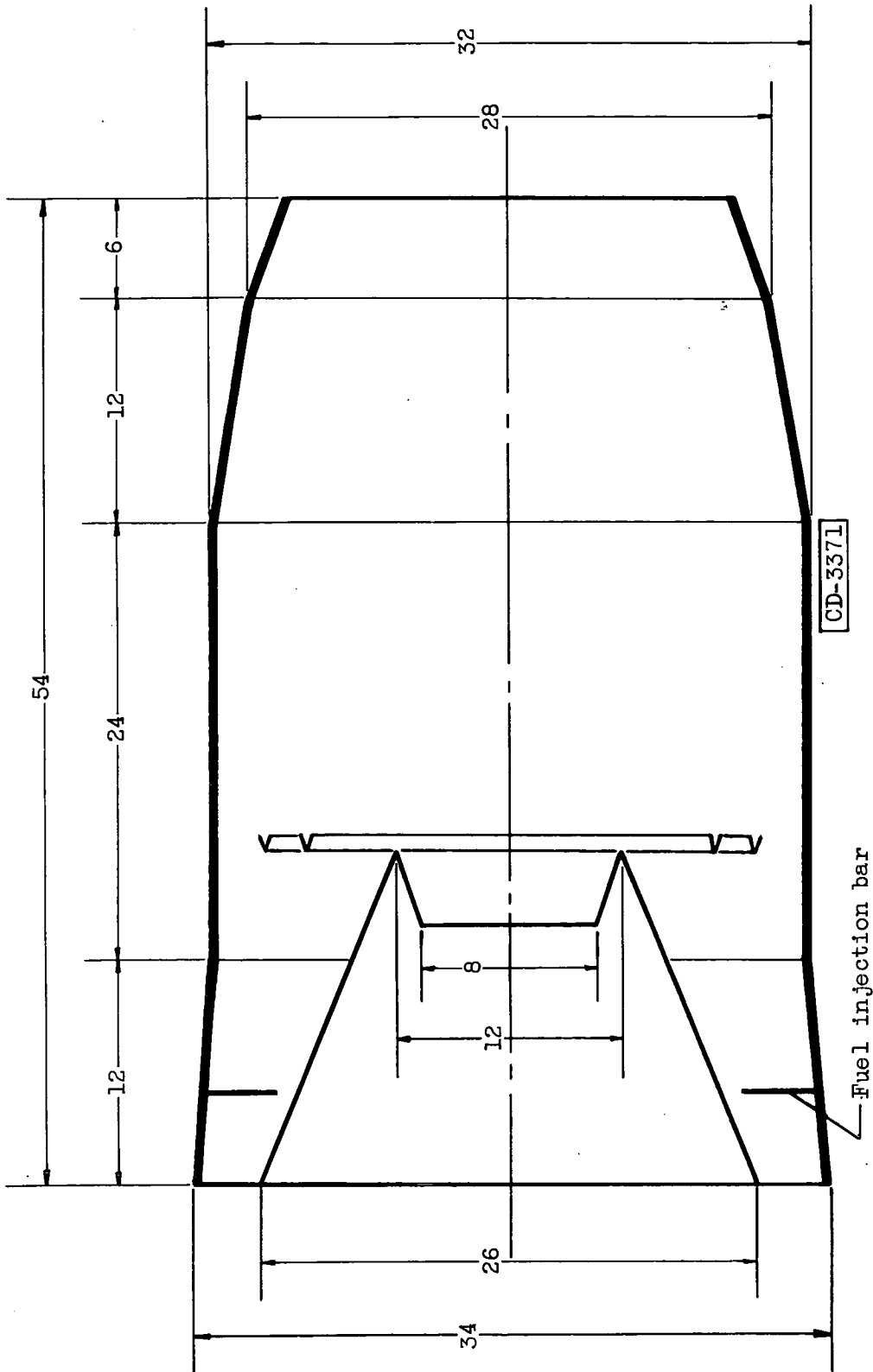


Figure 21. - Construction details of short afterburner configuration B. (All dimensions are in inches.)

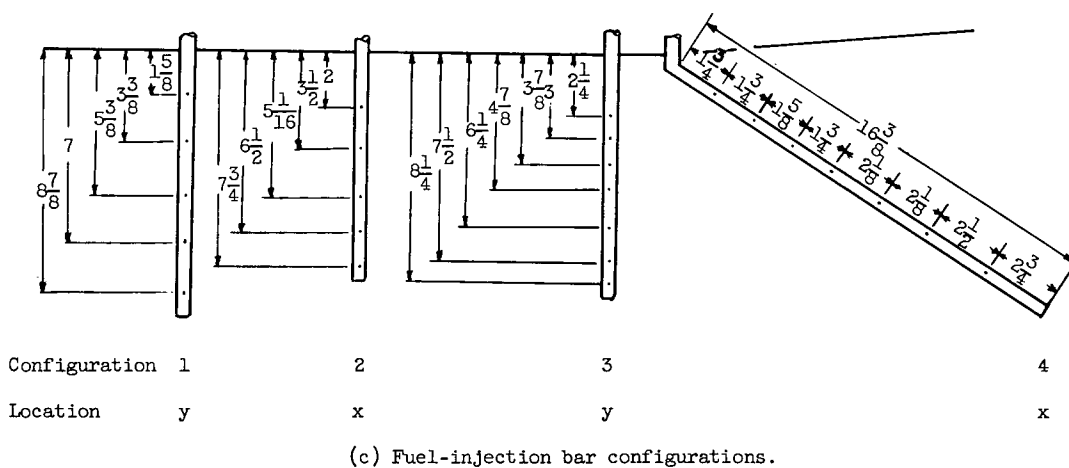
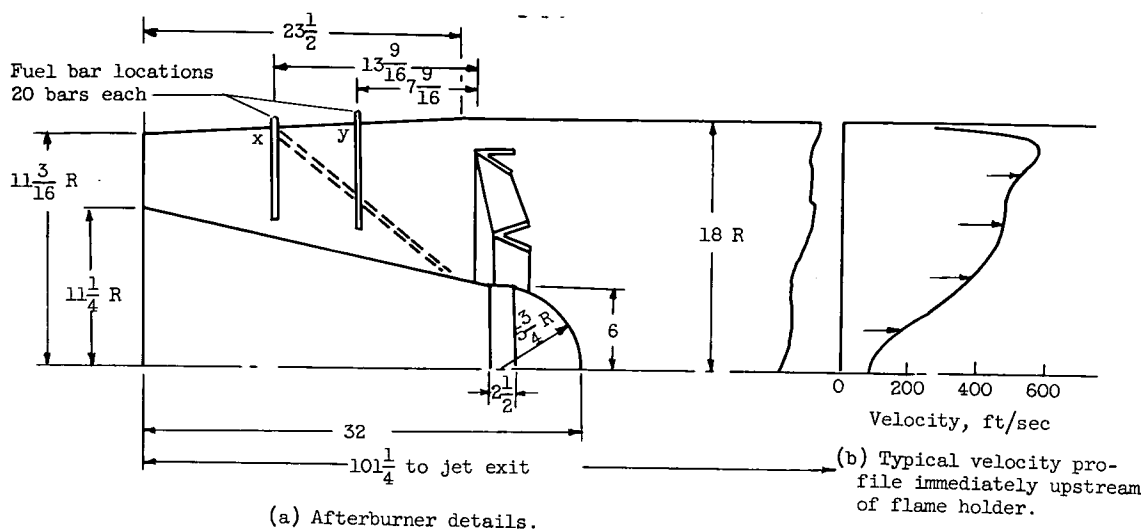


Figure 22. - Construction details of afterburner configuration C. (All dimensions are in inches.)

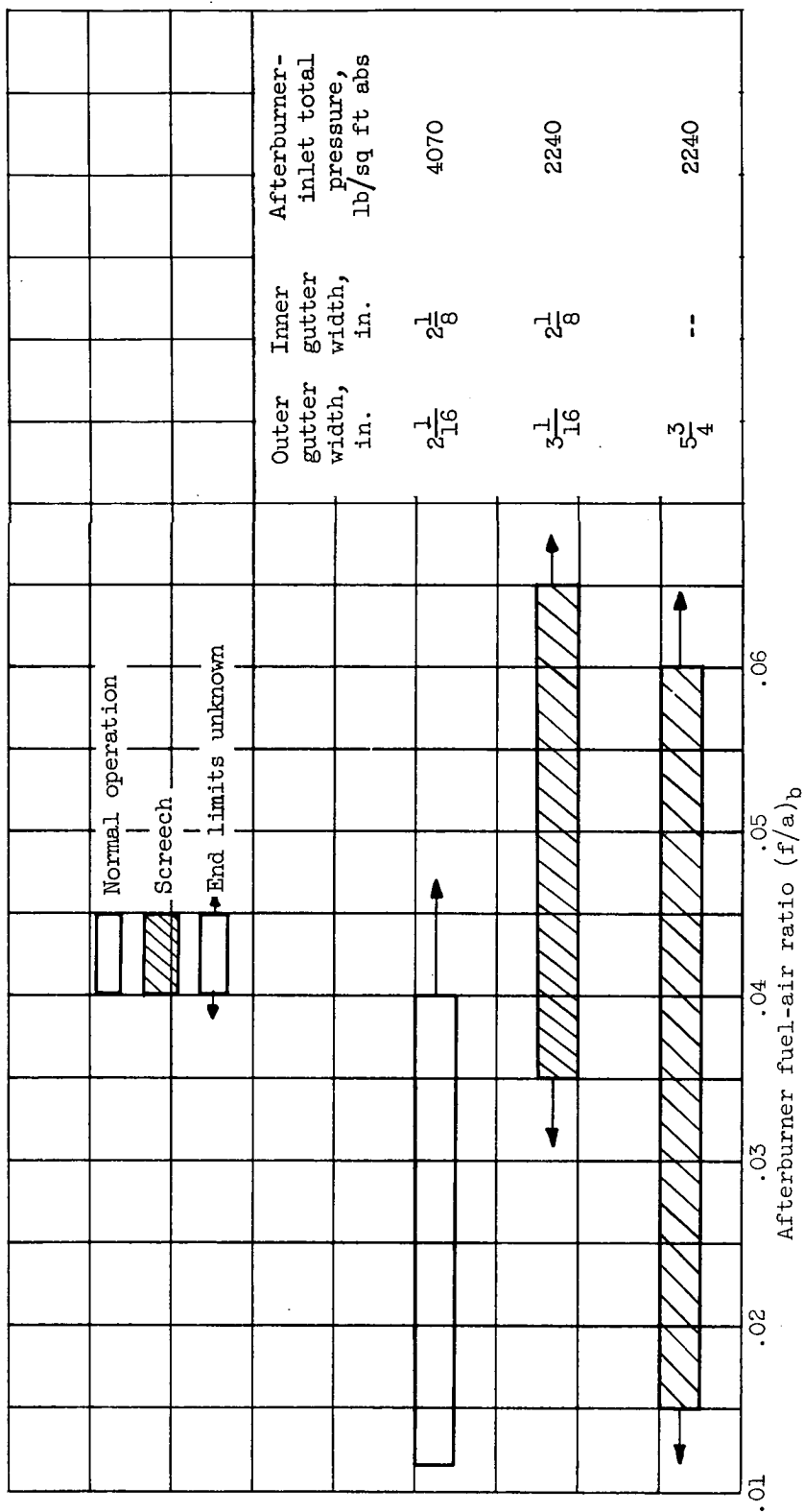


Figure 23. - Effect of flame-holder gutter width on screech limits, afterburner configuration A.

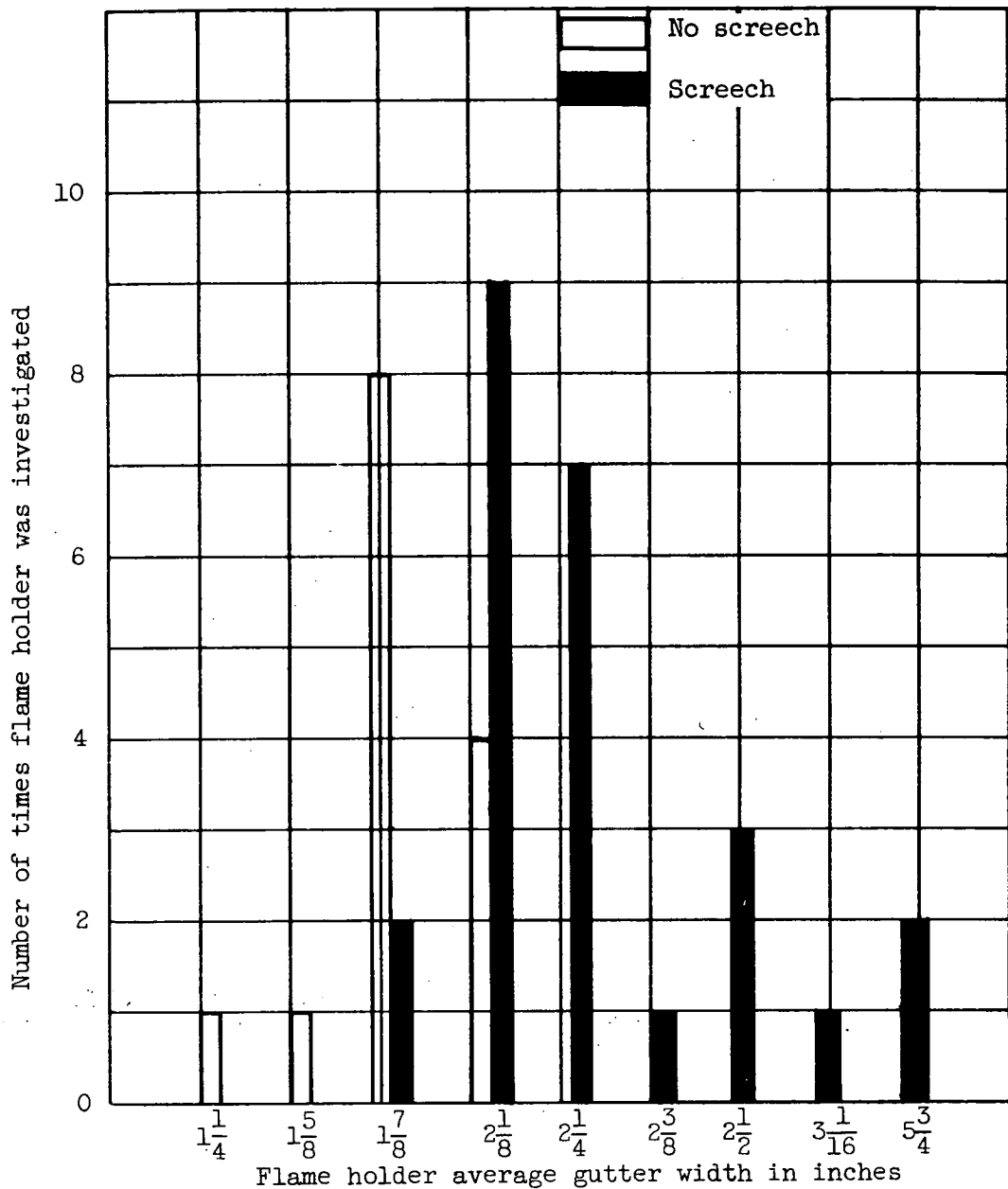


Figure 24. - Variation of flame-holder tendency to screech with gutter width at afterburner-inlet total pressures from 3850 to 4220 pounds per square foot absolute. Flame-holder blockage, 32 to 40 percent of flow area. Afterburner configuration A.

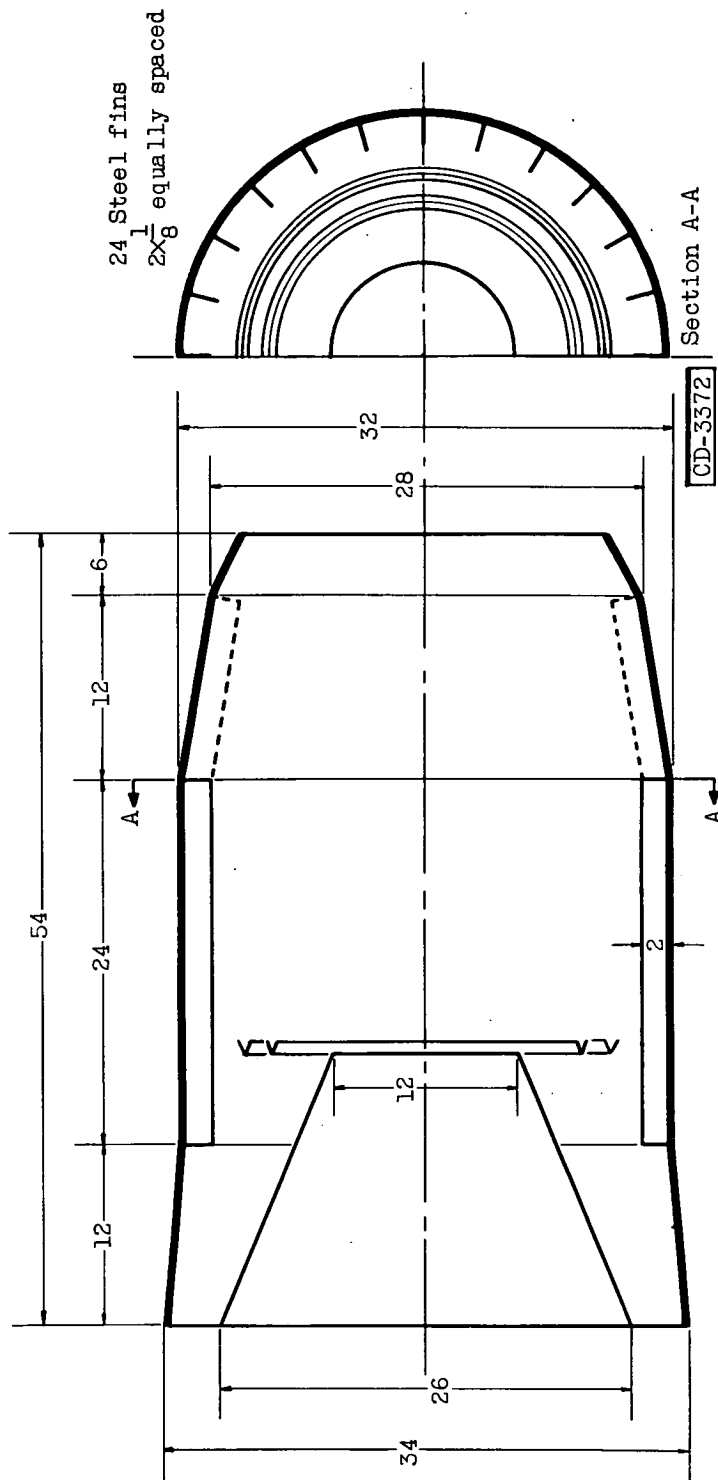
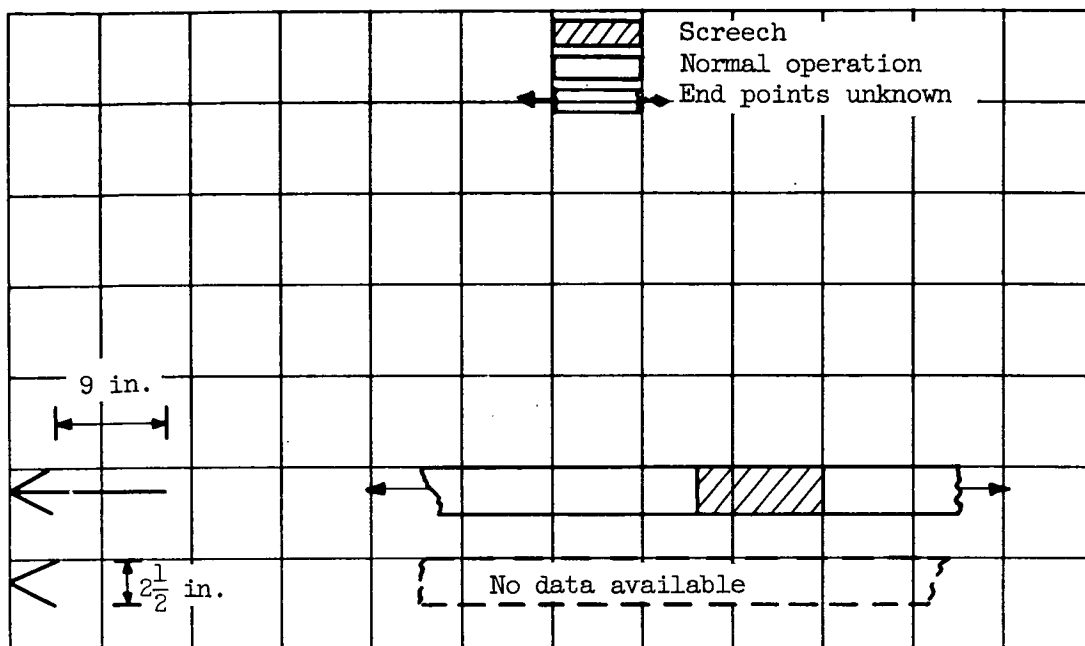
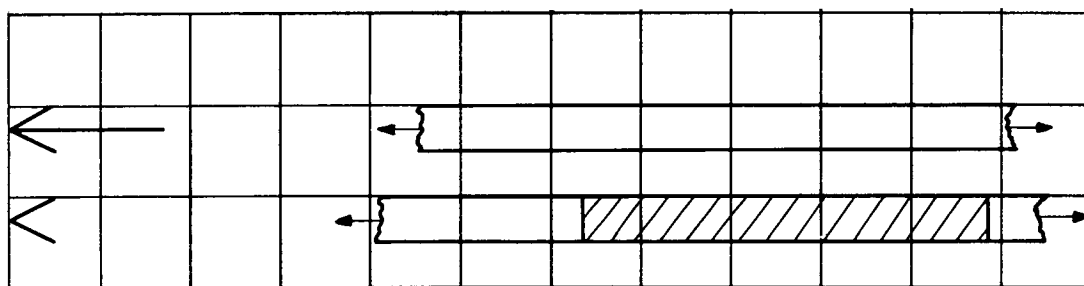


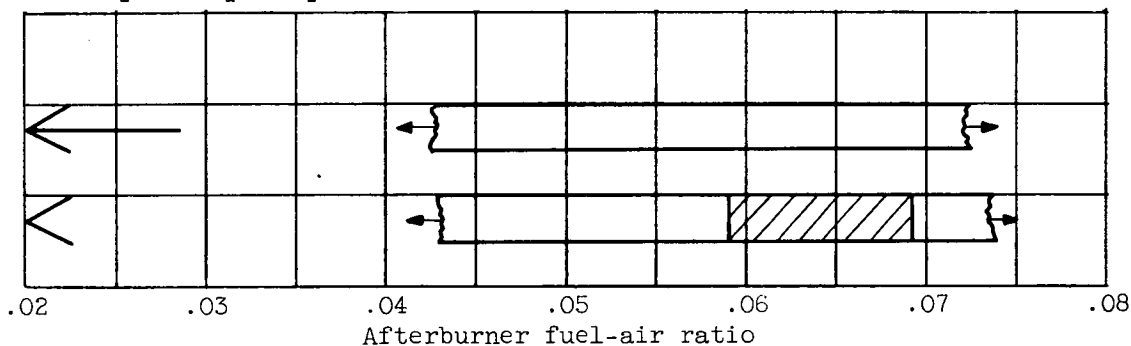
Figure 25. - Longitudinal fins installed in short afterburner configuration D. (All dimensions are in inches.)



(a) Air flow, 30 pounds per second; burner-inlet pressure, 1080 pounds per square foot.

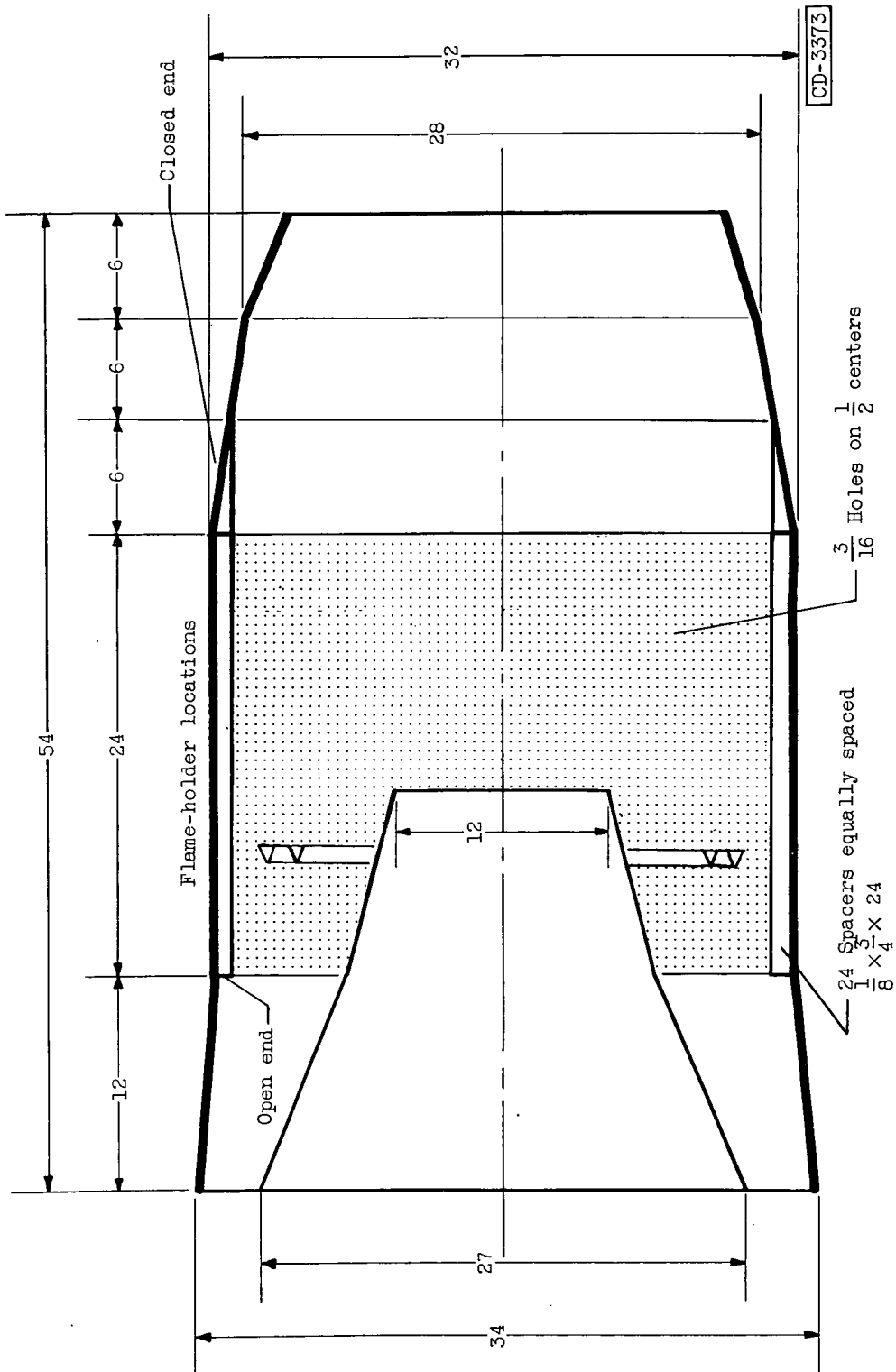


(b) Air flow, 20 pounds per second; burner-inlet pressure, 990 pounds per square foot.



(c) Air flow, 17.5 pounds per second; burner-inlet pressure, 870 pounds per square foot.

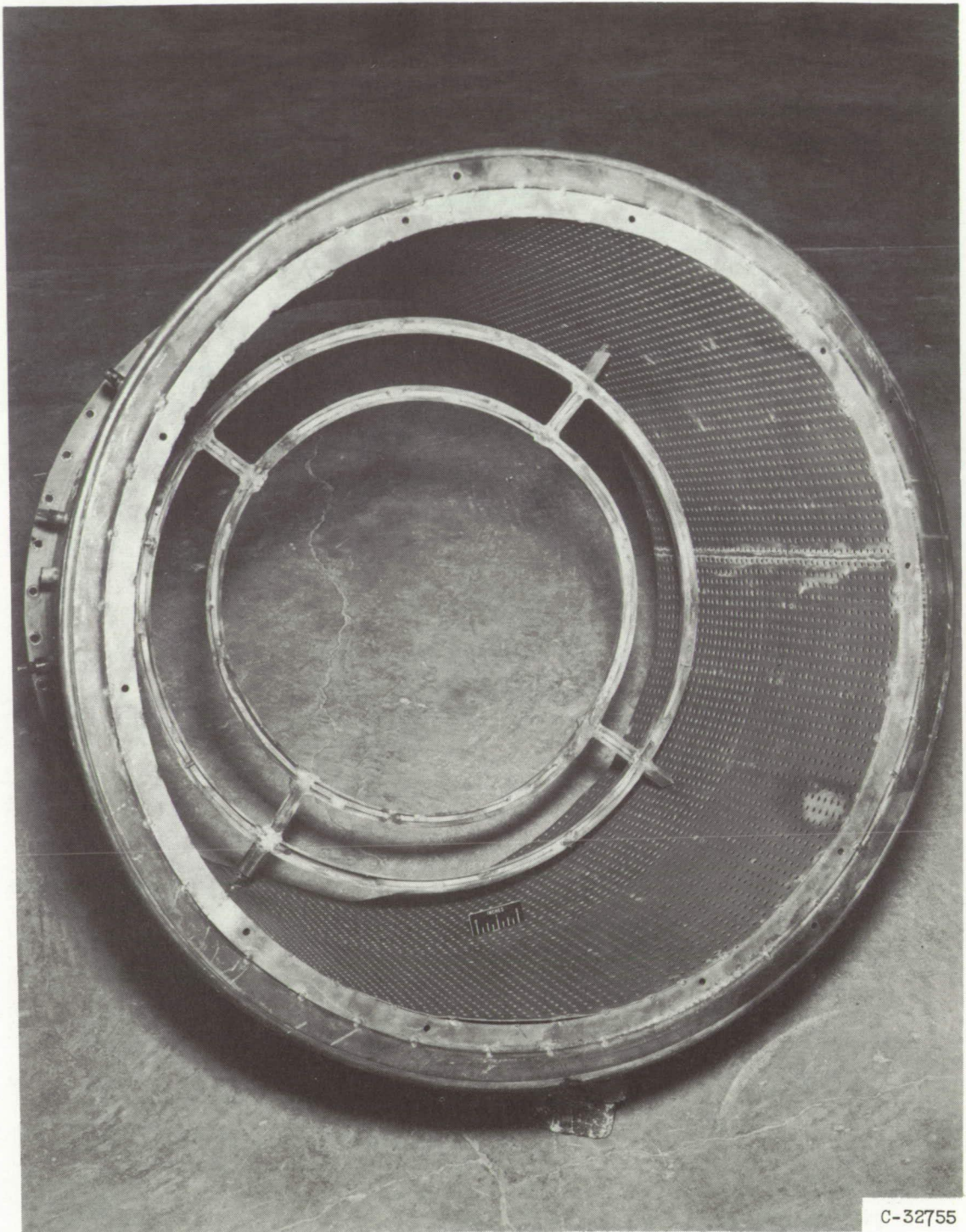
Figure 26. - Effect of splitter on screech limits of 26-inch diameter burner.



(a) Afterburner details showing perforated liner with  $\frac{3}{4}$ -inch-wide two-V-gutter flame holder having blocked area of 36 percent.

Figure 27. - Perforated liner installed in 32-inch-diameter afterburner configuration E.  
(All dimensions are in inches.)





(b) Photograph of perforated liner installation.

Figure 27. - Perforated liner installed in 32-inch-diameter afterburner, configuration E.

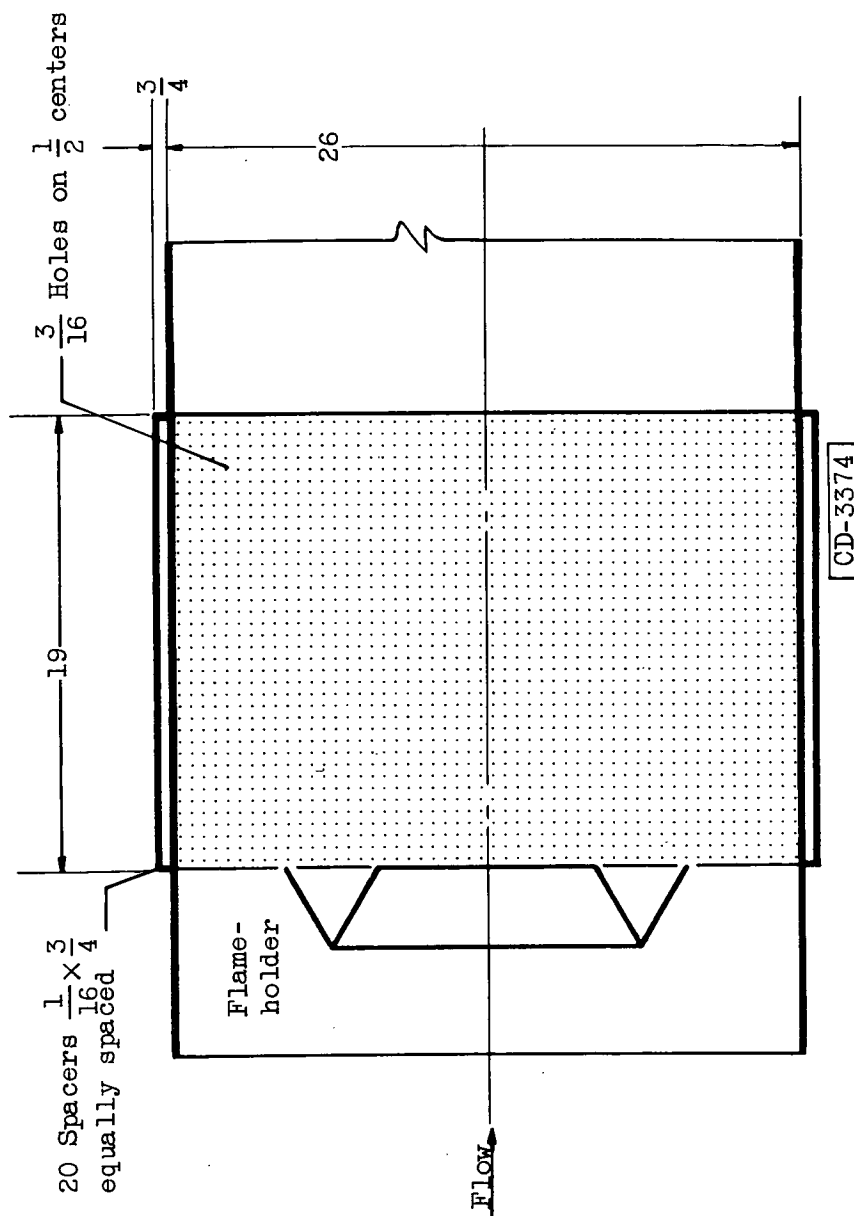


Figure 28. - Construction details of perforated liner installed in 26-inch-diameter combustor with  $4\frac{1}{2}$ -inch-wide V-gutter flame holder having blocked area of 36 percent. (All dimensions are in inches.)

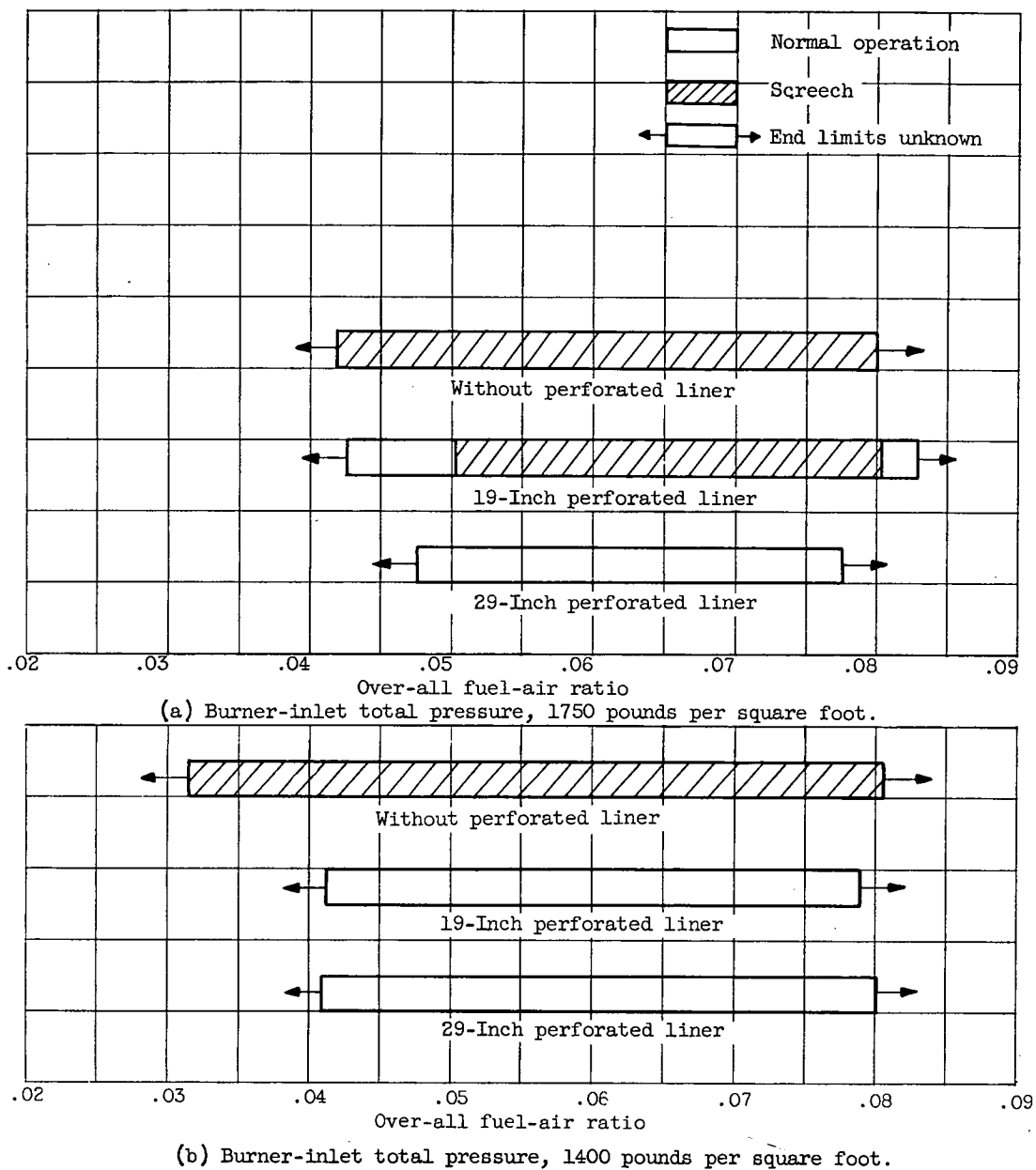


Figure 29. - Effect of perforated liner on screech limits in 26-inch-diameter duct configuration E.



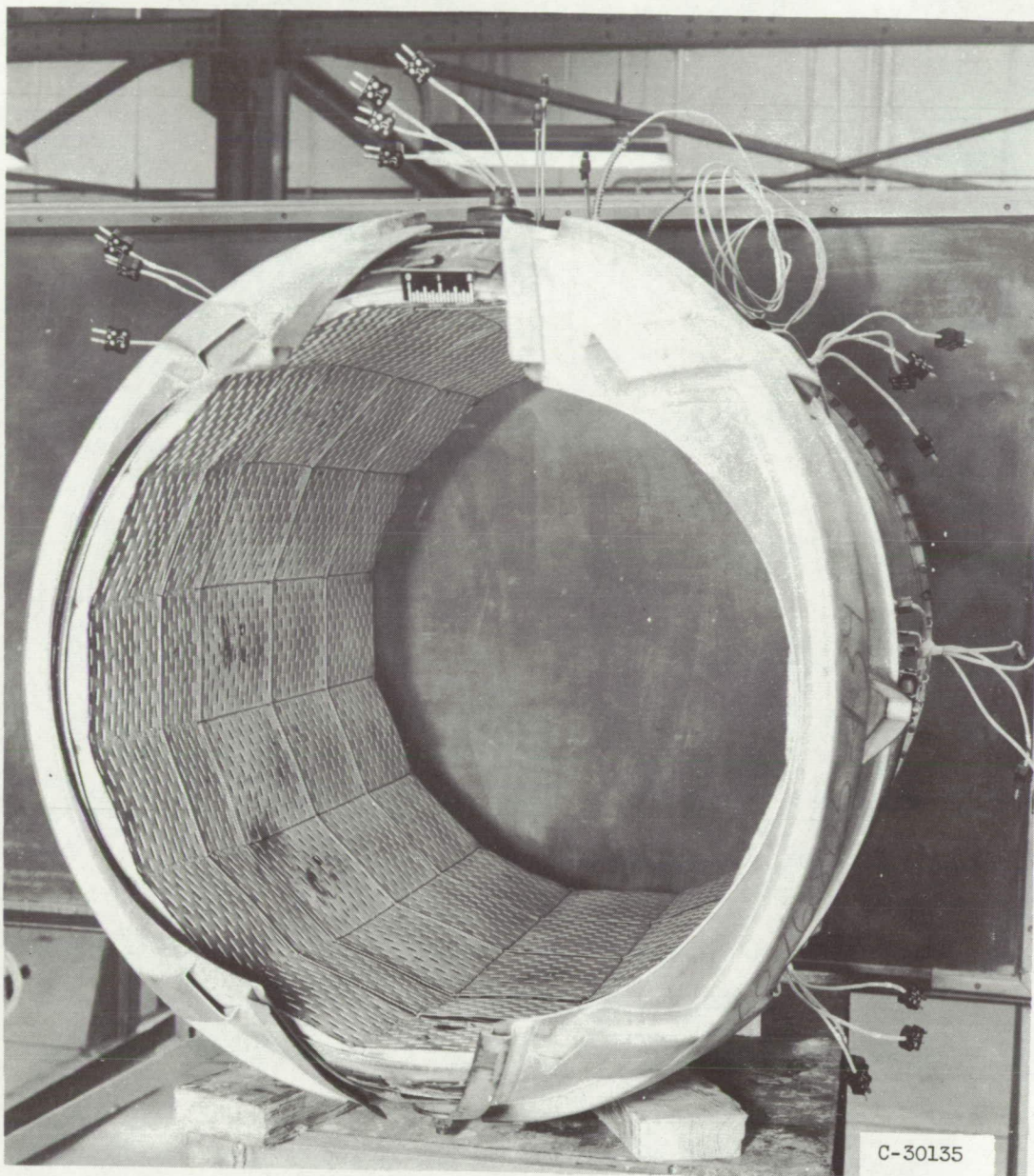


Figure 30. - Louvered cooling liner.



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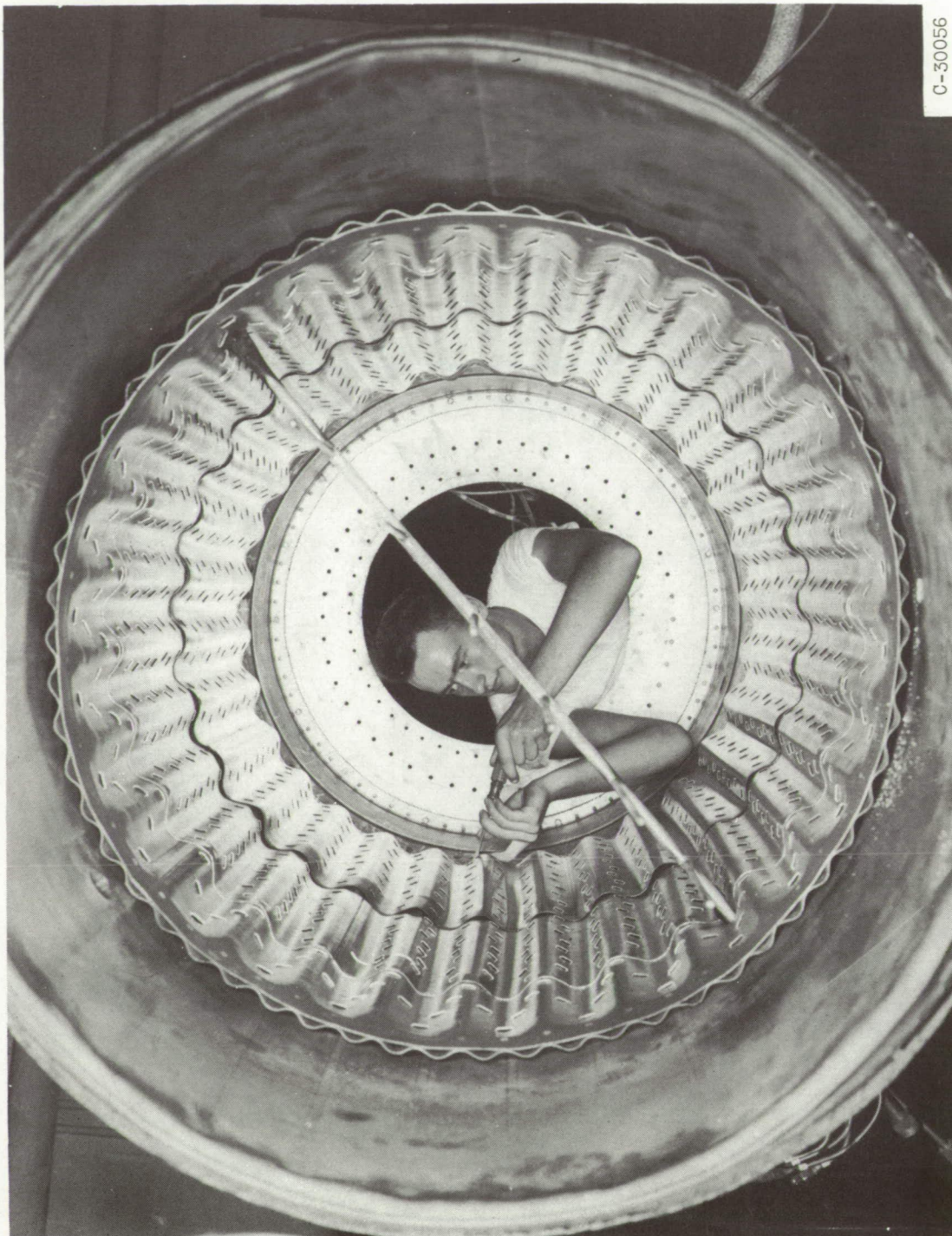


Figure 31. - Corrugated-louvered cooling liner.

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